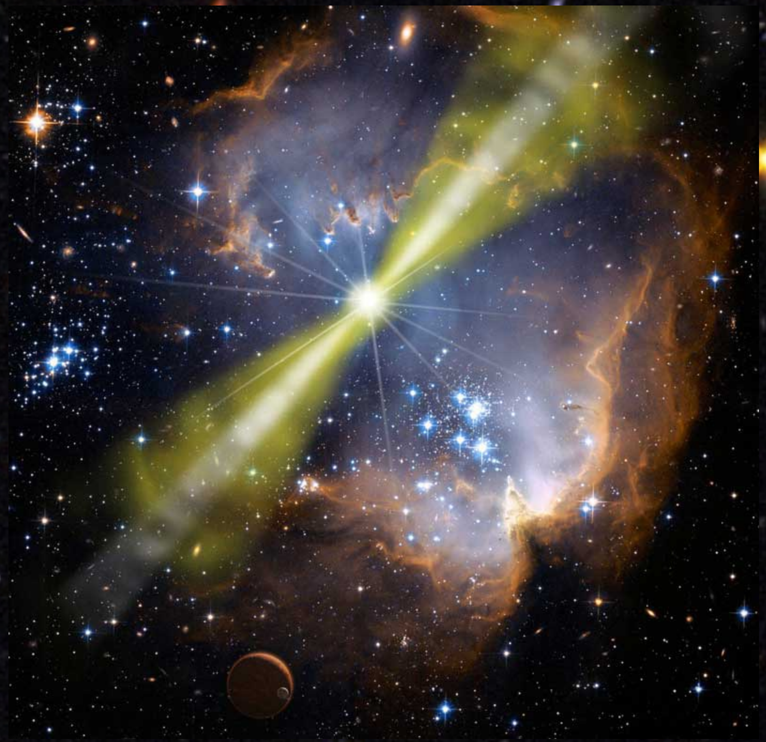
Very-high-energy gamma-rays from low-luminosity (short) GRBs

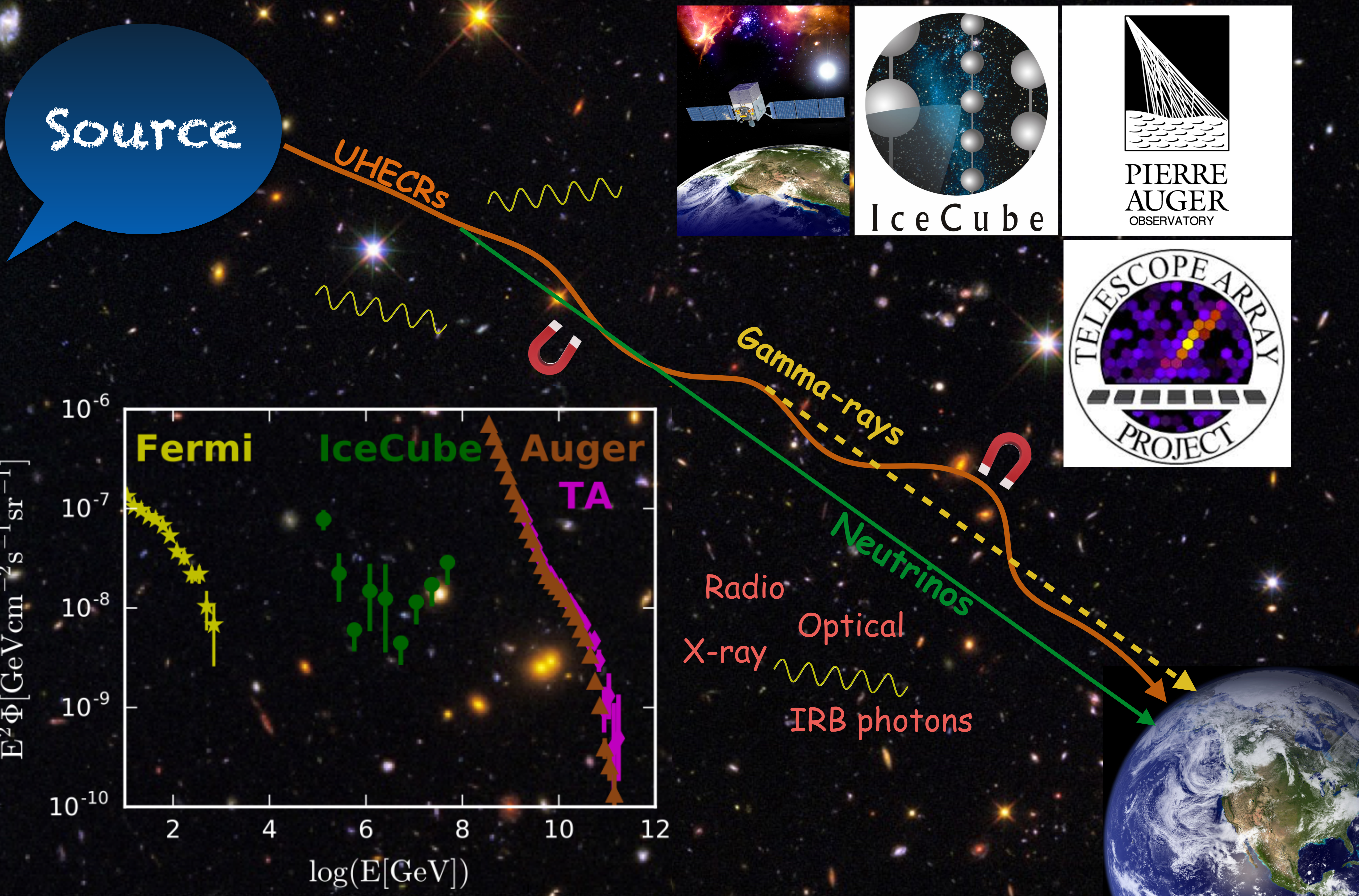


Bing Theodore Zhang

YITP, Kyoto

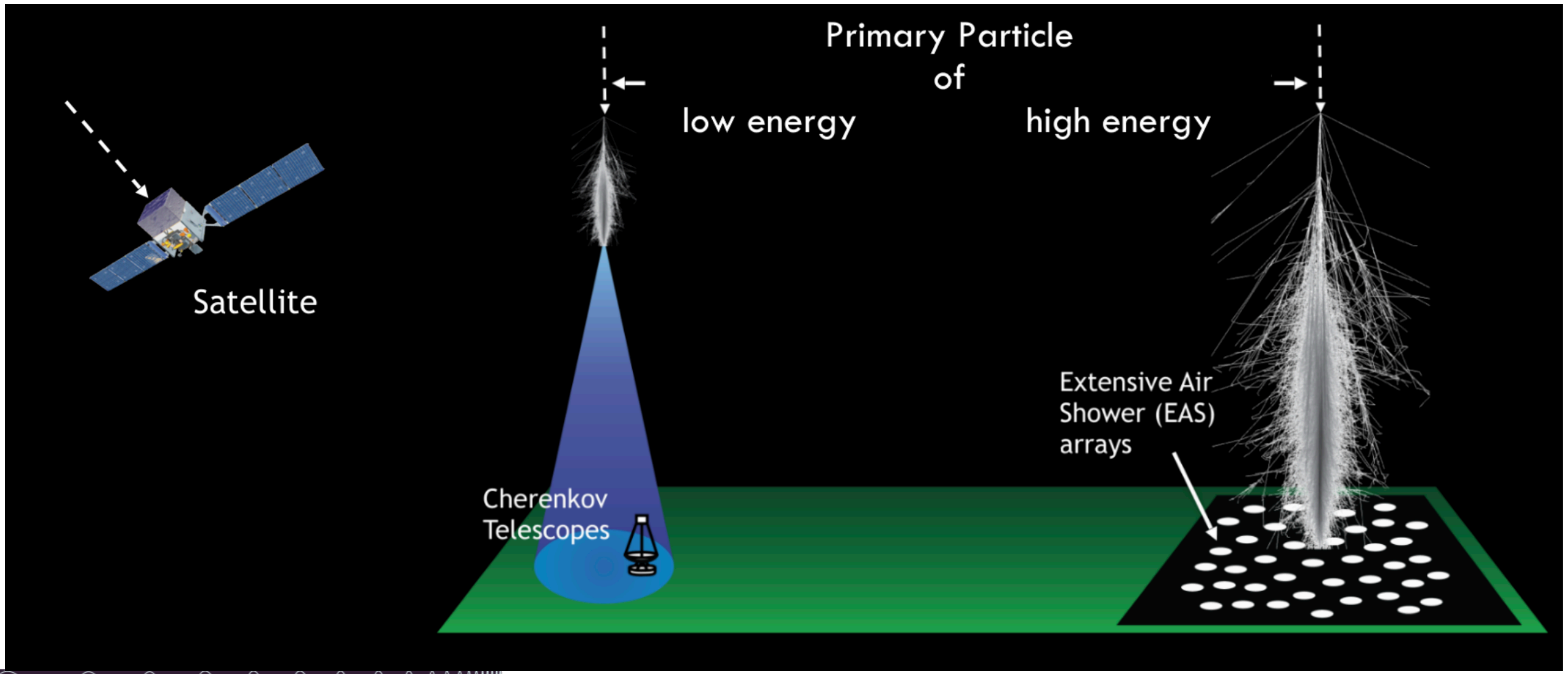
Jun 7 2022

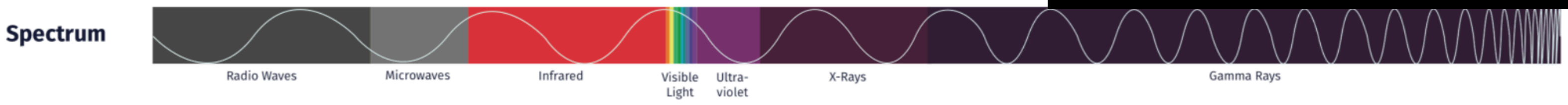
Multi-messenger Astronomy



Very-High-Energy (VHE) gamma-rays

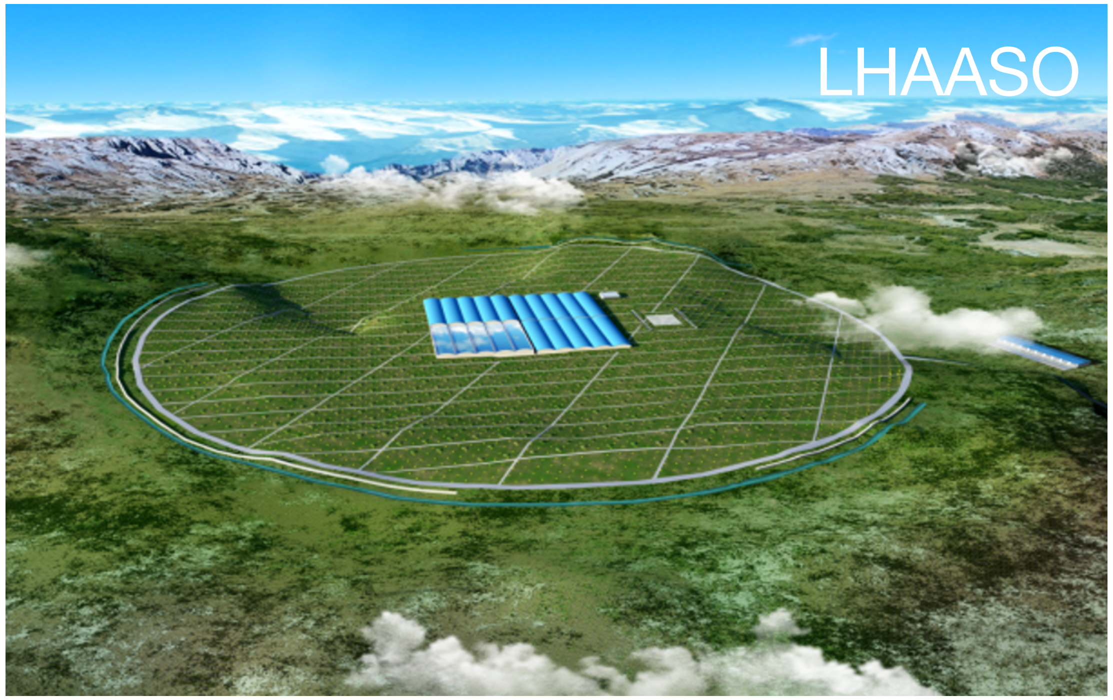
The detection of very-high-energy gamma-rays (> 0.1 GeV)





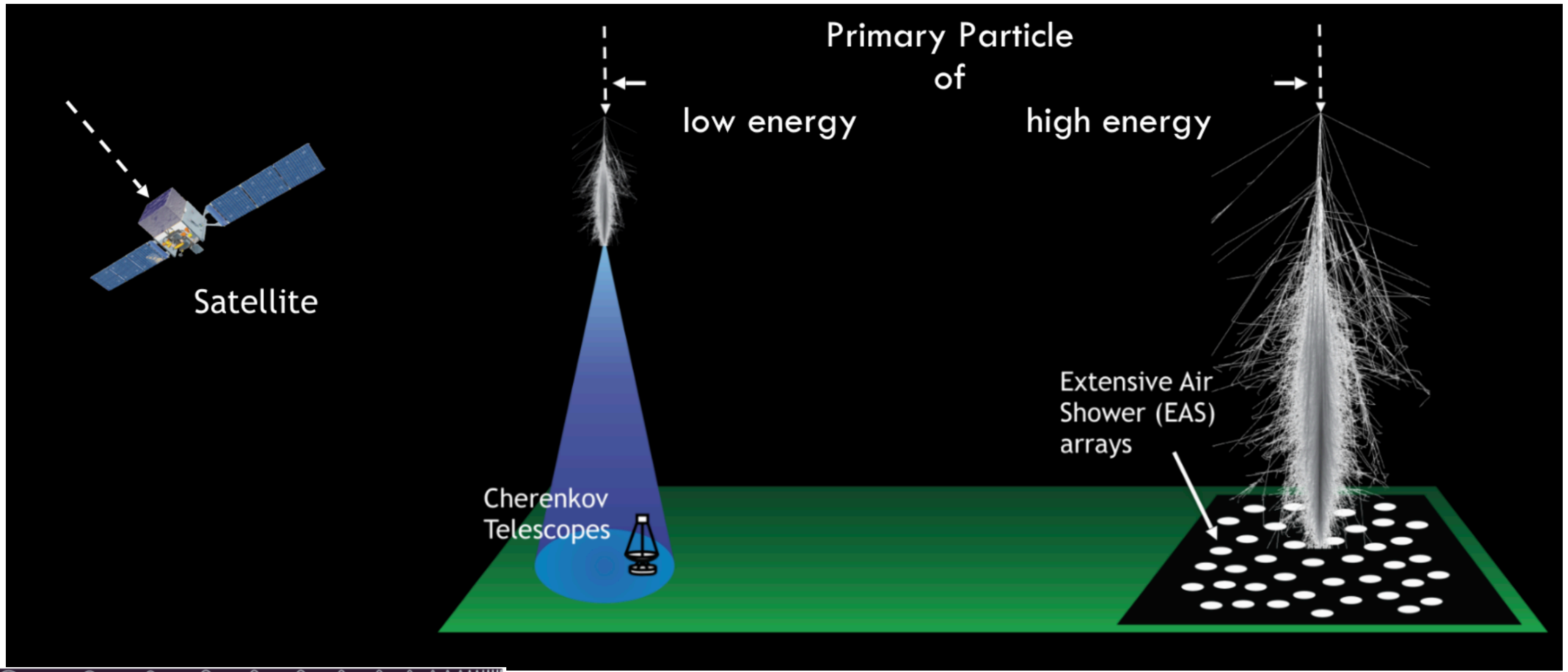
From Laura Peres

~GeV ~TeV ~ 100 TeV



Very-High-Energy (VHE) gamma-rays

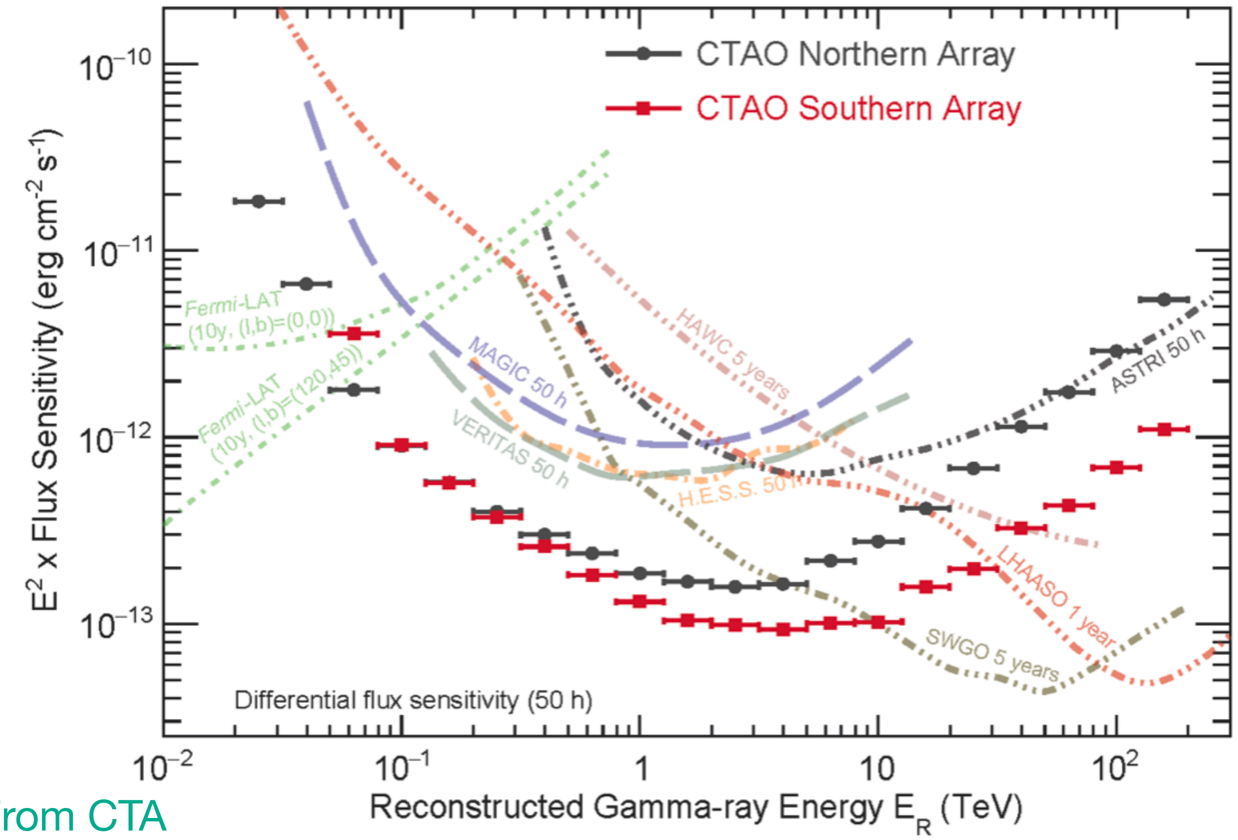
The detection of very-high-energy gamma-rays (> 0.1 GeV)



From Laura Peres

~GeV ~TeV ~ 100 TeV

The sensitivity curve

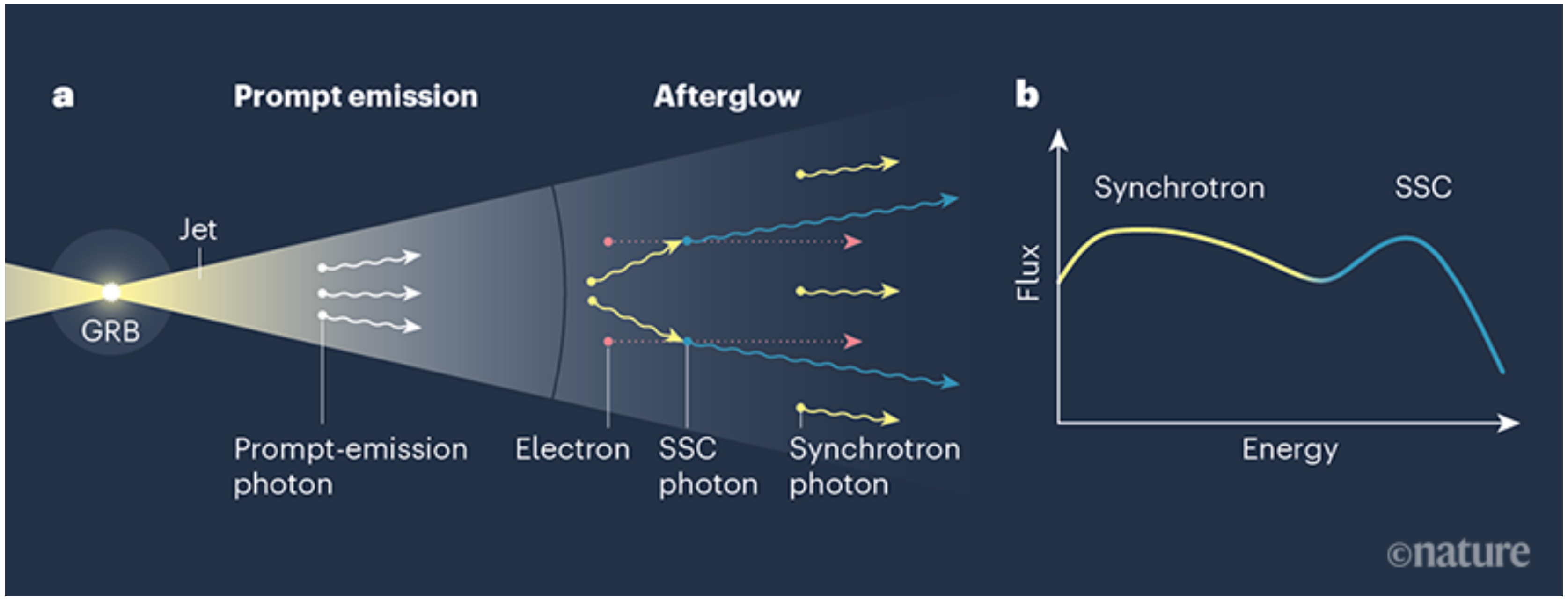


From CTA

VHE gamma-rays from GRBs

The synchrotron self-Compton is the preferred explanation for the observed spectral energy distribution

First detected at 2019



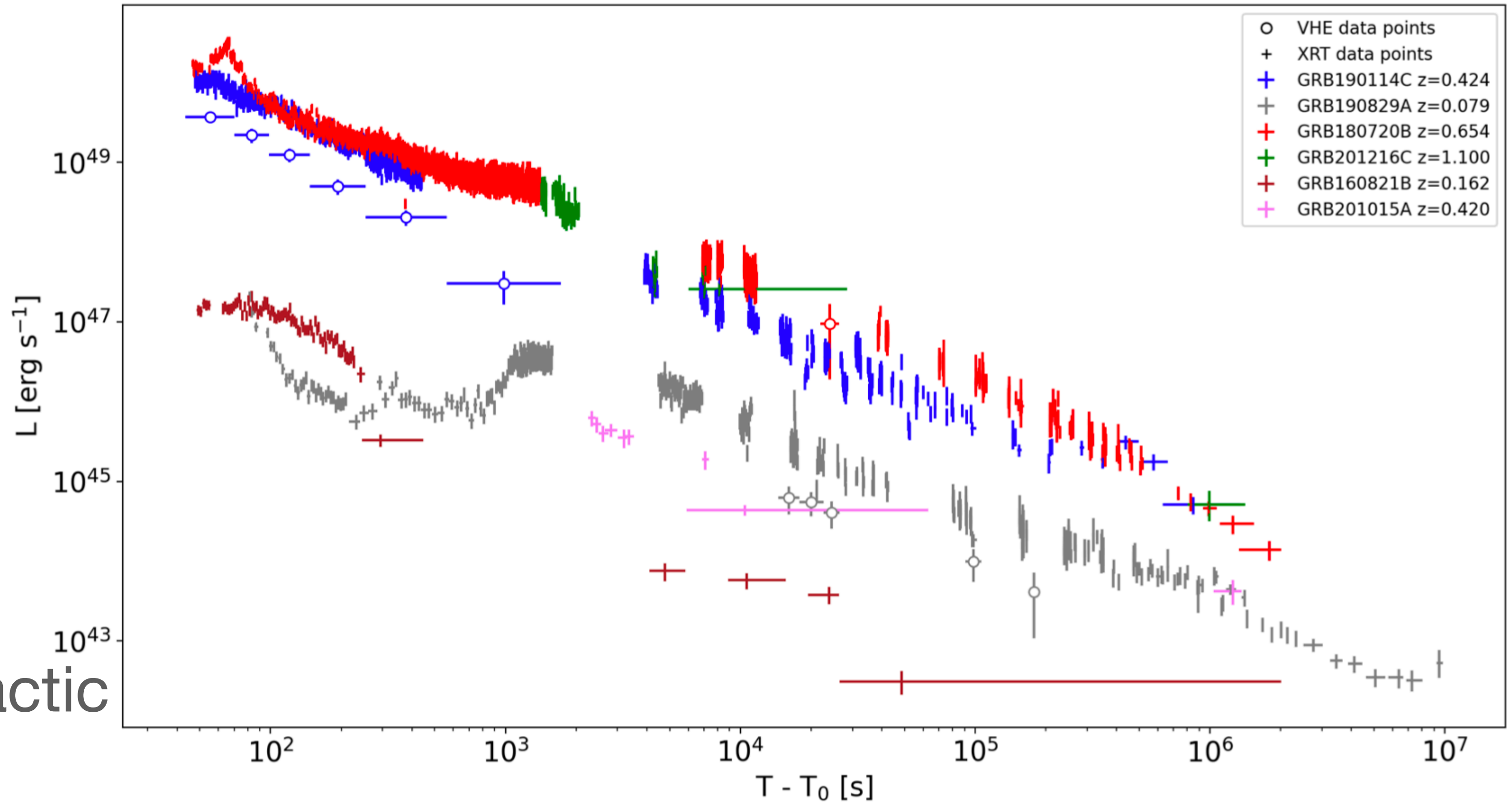
Zhang 2019

Observing conditions

Night, good whether

Bright, energetic events
- Provide enough VHE photons

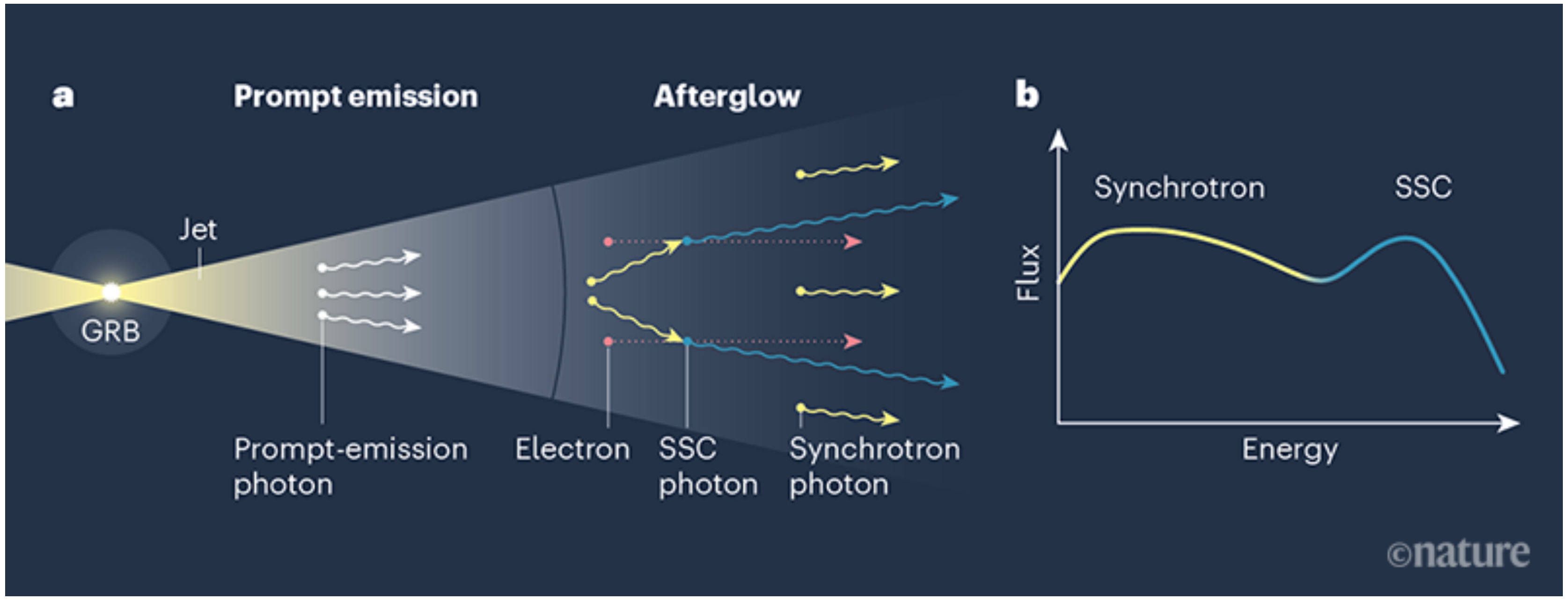
Nearby, low redshift
- Avoid absorption by Extragalactic background light (EBL)



Miceli and Nava, 2022

VHE gamma-rays from GRBs

The synchrotron self-Compton is the preferred explanation for the observed spectral energy distribution



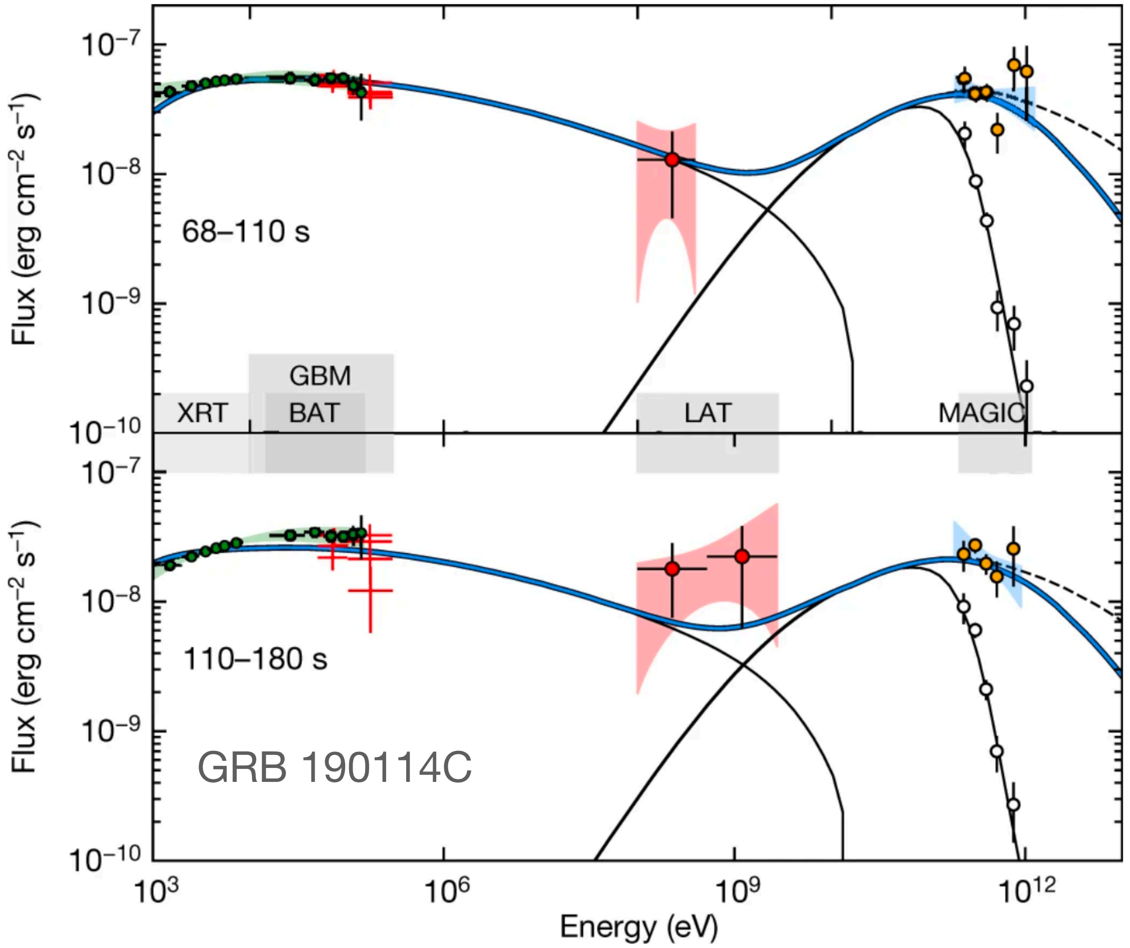
Zhang 2019

Implications for the microphysics

The value of epsilon_e ~ 0.1

The value of epsilon_B ~ 1E-5 - 1E-3

Large values of epsilon_B ~ 0.01 - 0.1 was excluded



MAGIC Colla, 2019

VHE gamma-rays from GRBs

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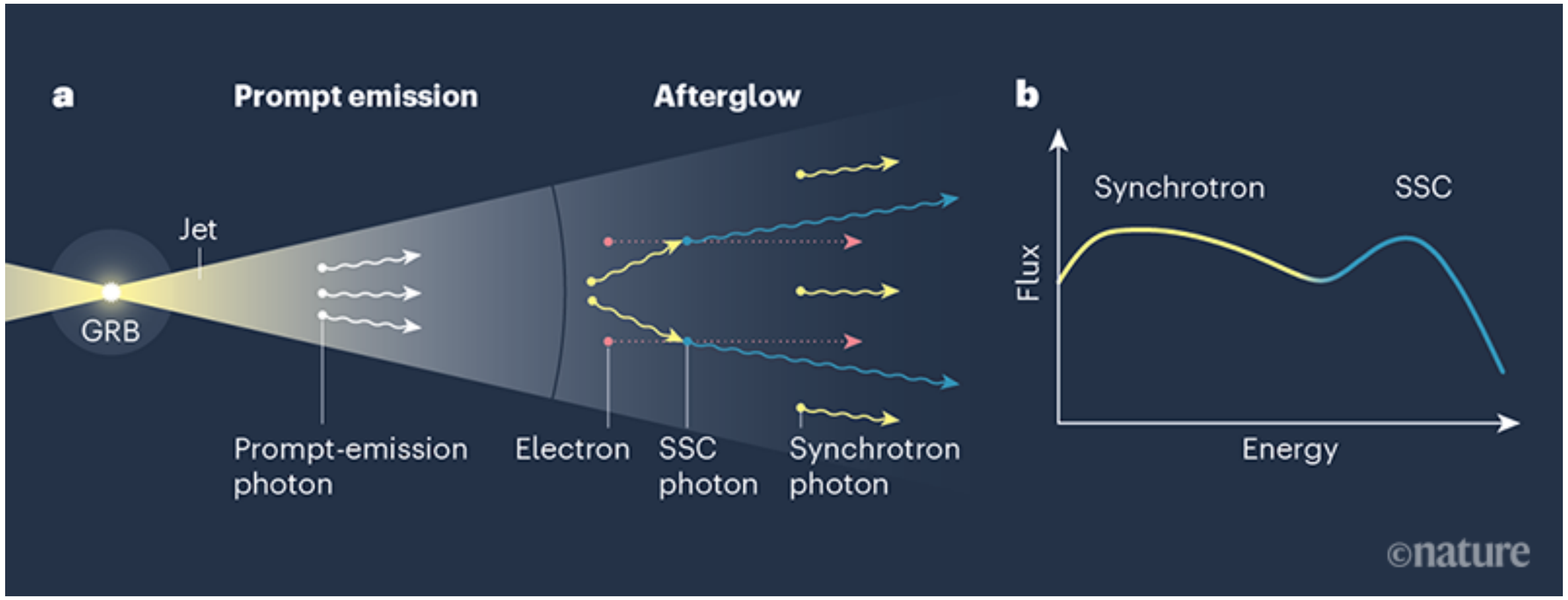


Zhang 2019

Implications for the microphysics

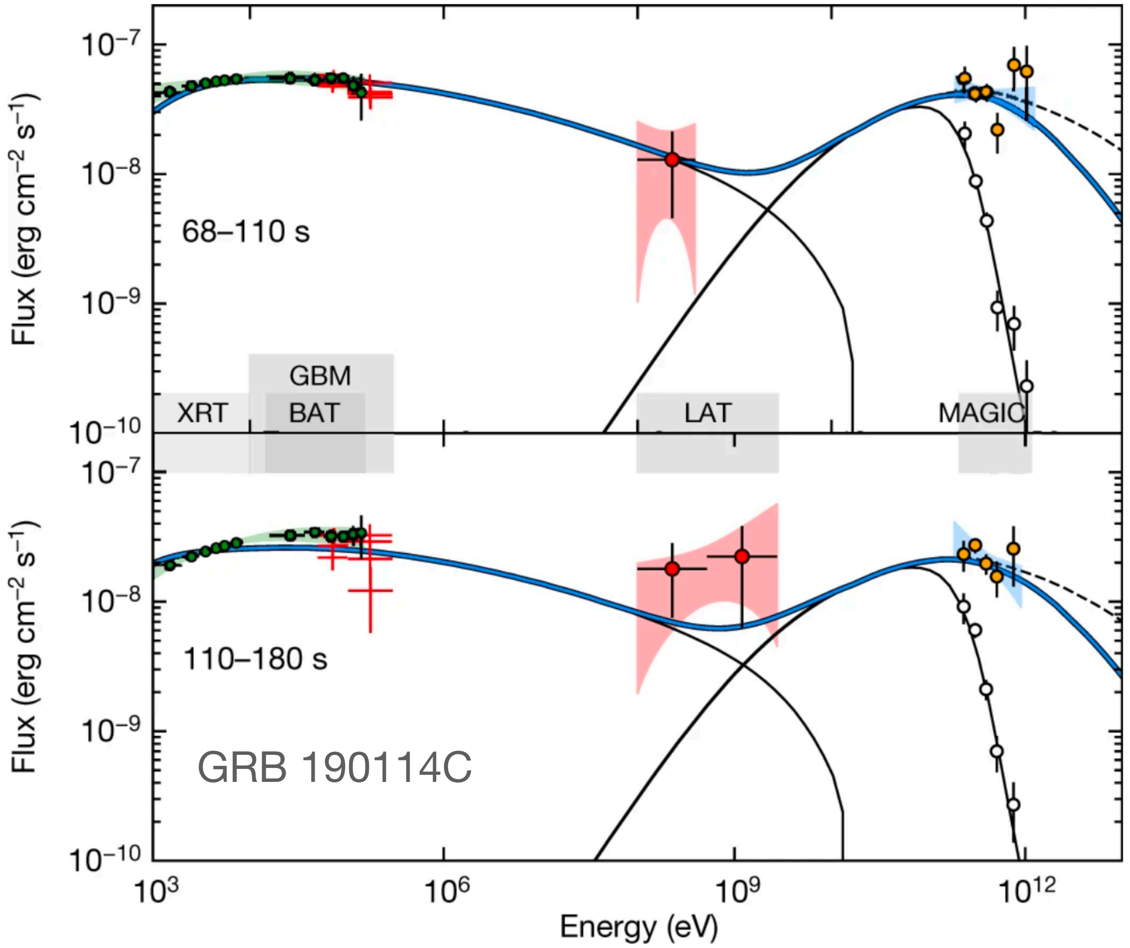
The value of epsilon_e ~ 0.1

The value of epsilon_B ~ 1E-5 - 1E-3

Large values of epsilon_B ~ 0.01 - 0.1 was excluded

Variation of epsilon_e and epsilon_B?

Misar et al, 2021



MAGIC Colla, 2019

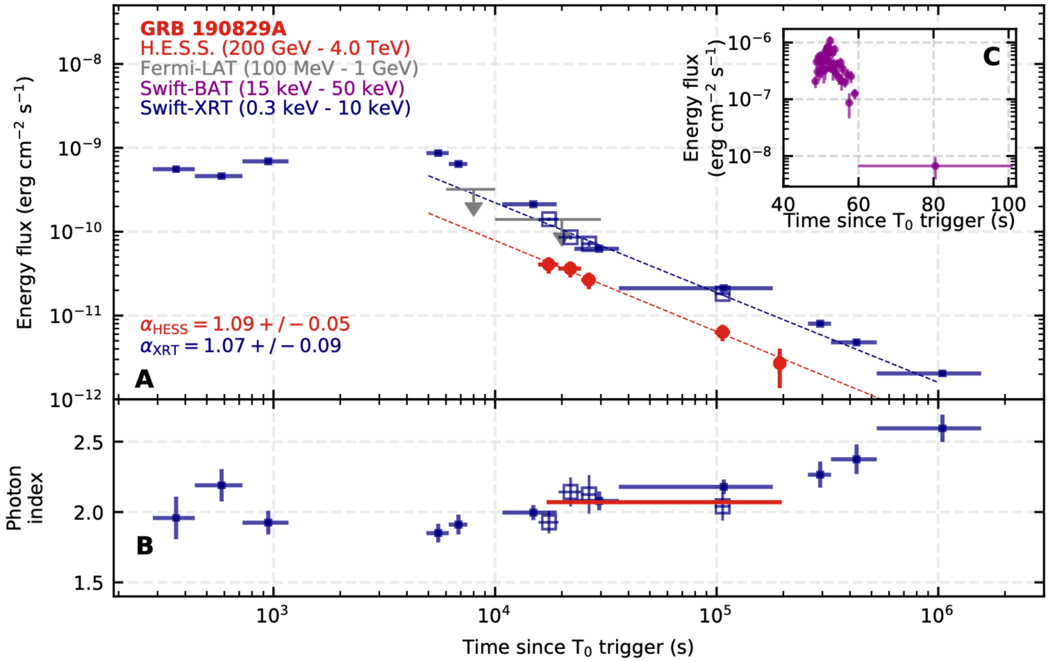
VHE gamma-rays from Low-luminosity (short) GRBs?

VHE gamma-rays from low-luminosity GRB? Yes!

Low-luminosity GRBs are promising sources of ultrahigh-energy cosmic ray nuclei!

GRB 190829A

Detected by H.E.S.S. > 5 sigma



The H.E.S.S. Collaboration, 2021

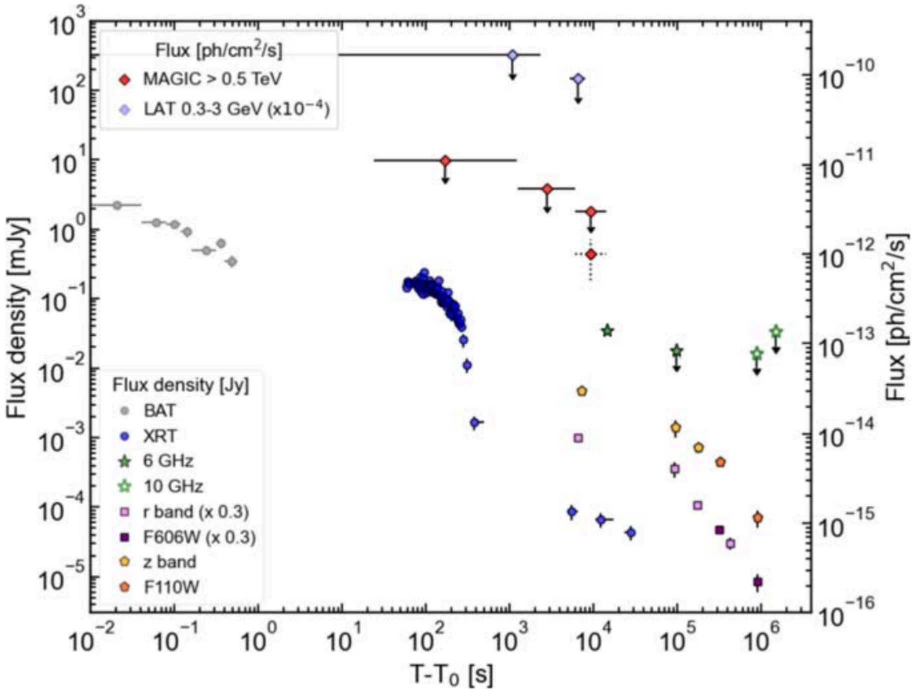
VHE gamma-rays from short GRB? Yes?

e.g. GRB 170817A / GW 170817A, Gravitational sources

E.g. Murase et al, 2018

GRB 160821B

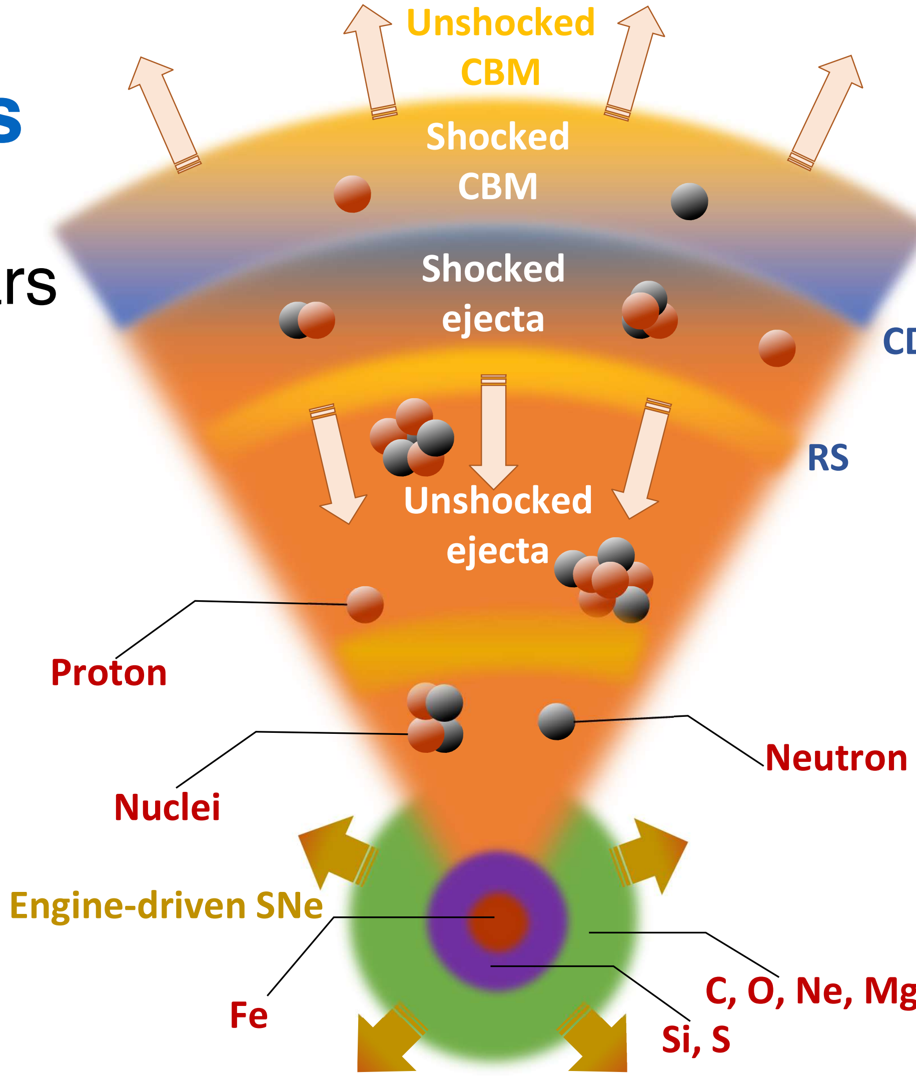
Detected by MAGIC > 3 sigma



The MAGIC Collaboration, 2021

UHE cosmic ray nuclei from low-luminosity GRB

GRBs are related to the deaths of massive stars



Nuclei can be extracted from the interior of massive stars

See, Horiuchi, Murase, Ioka, Meszaros, 2012, ApJ

Murase, Ioka, Nagataki, Nakamura, 2008, PRD

Wang, Razzaque, Meszaros, 2008, PRD

High-luminosity GRBs Eg. Waxman, 1995, PRL

- The HL GRB - HE neutrinos connection are disfavored by IcuCube
- Nuclei are disintegrated at the engine for HL GRBs (such as, fireball model)

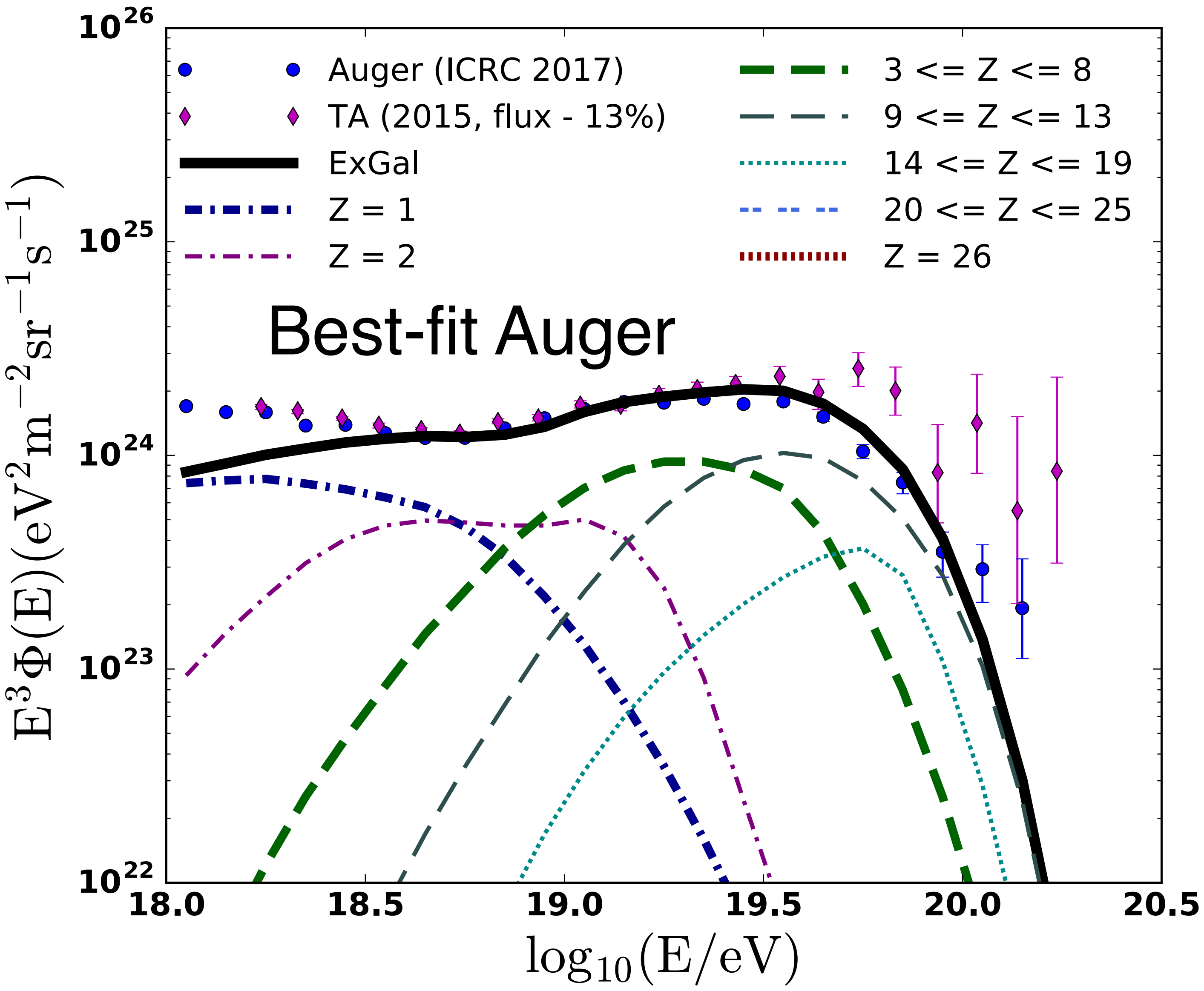
Low-luminosity GRBs

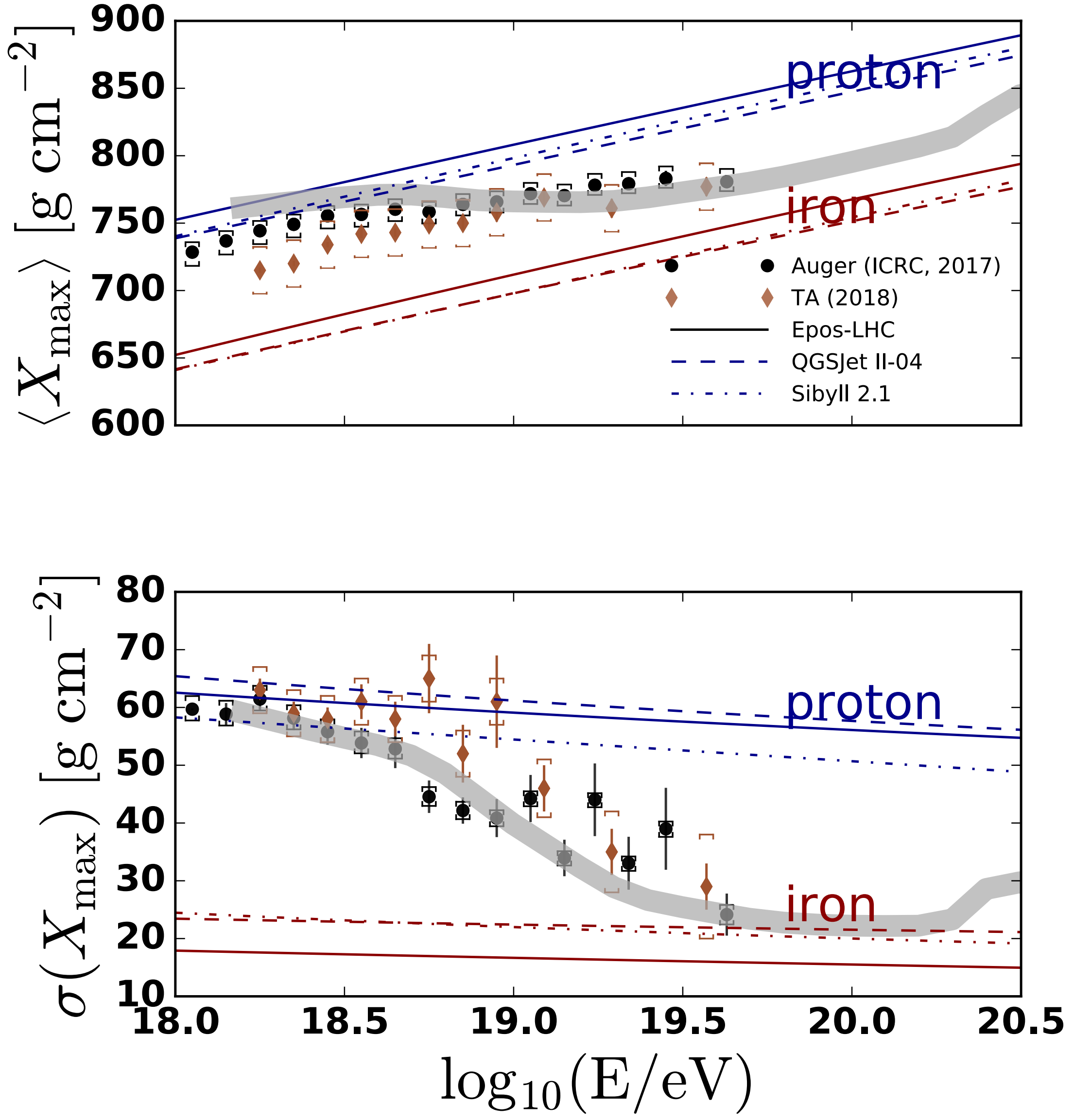
- Source rate much higher than HL GRBs
- The LL GRB - HE neutrinos connection are still possible
- Nuclei can survive at the engine for LL GRBs

Murase, Ioka, Nagataki, Nakamura, 2008, PRD Liu, Wang, Dai, 2011, MNRAS

BTZ, Murase, Kimura, Horiuchi, Meszaros, 2018, PRD Boncioli, Biehl, Winter, 2018

UHE cosmic ray nuclei from low-luminosity GRB





Outflow: relativistic jet $E^{\rm esc}_{p,\max} = 10^{18.3}\ \mathrm{eV}$ $\boxed{\mathrm{O} :\sim 60\% \quad \mathrm{Si} :\sim 35\% \quad \mathrm{S} :\sim 5\%}$

Model Jet-B: Homogeneous CBM $\varrho_{\rm cbm} = 1\ \mathrm{cm}^{-3}$

Silicon-rich composition

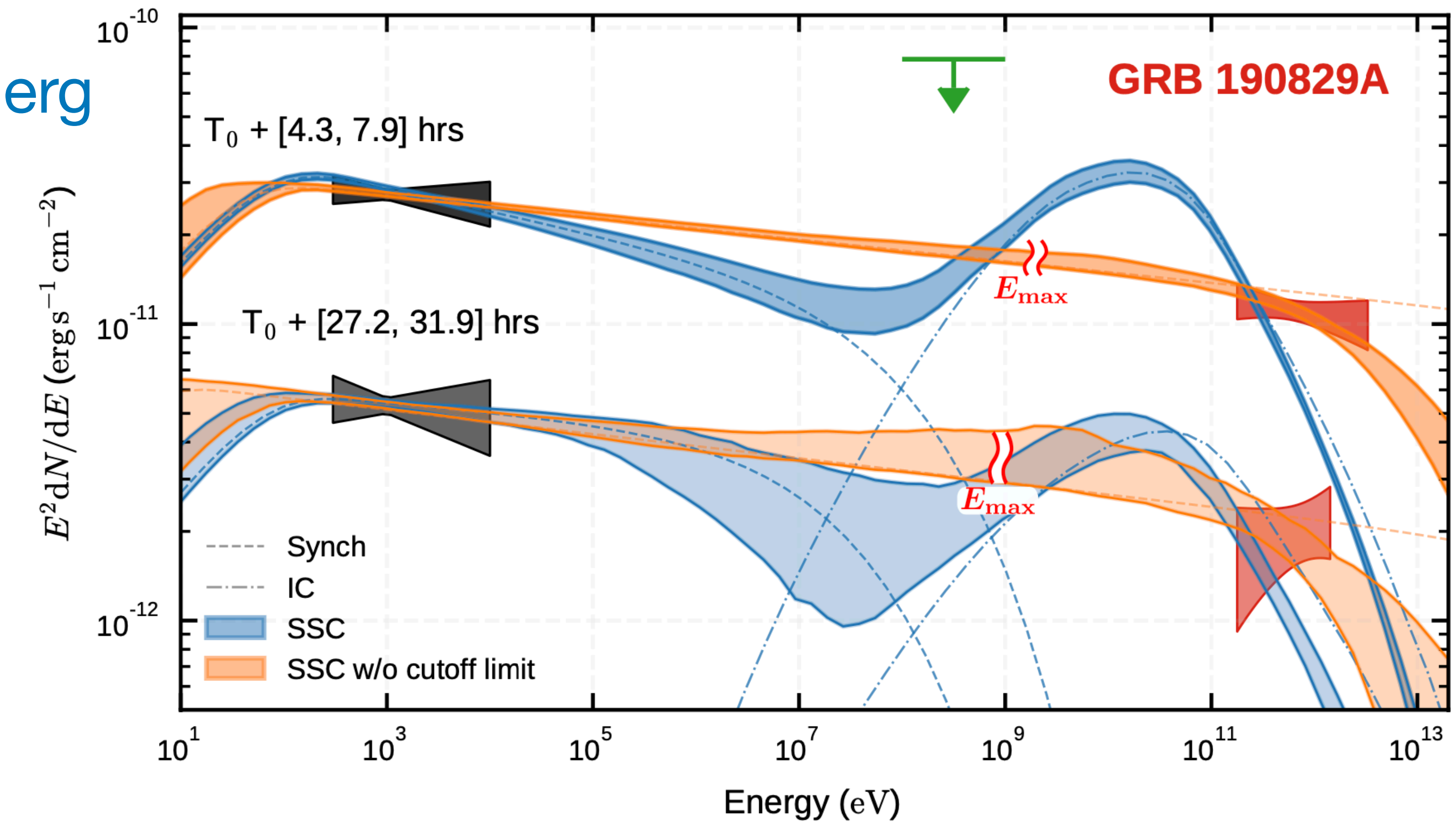
Can fit the Auger data very well

GRB 190829A - VHE gamma-rays

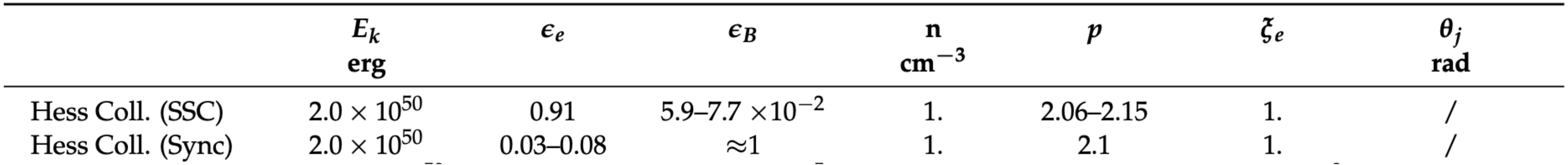
The prompt emission energy ~ 10^50 erg

The standard SSC model failed to explain the SED

Synchrotron emission? Limited by maximum electron energy



The H.E.S.S. collaboration 2021



	E_k erg	ϵ_e	ϵ_B	n cm^{-3}	p	ξ_e	θ_j rad
Hess Coll. (SSC)	2.0×10^{50}	0.91	5.9–7.7 $\times 10^{-2}$	1.	2.06–2.15	1.	/
Hess Coll. (Sync)	2.0×10^{50}	0.03–0.08	≈1	1.	2.1	1.	/

Melici and Nava, 2022

GRB 190829A - External-inverse Compton scenario

Seed photons from long-lasting central engine

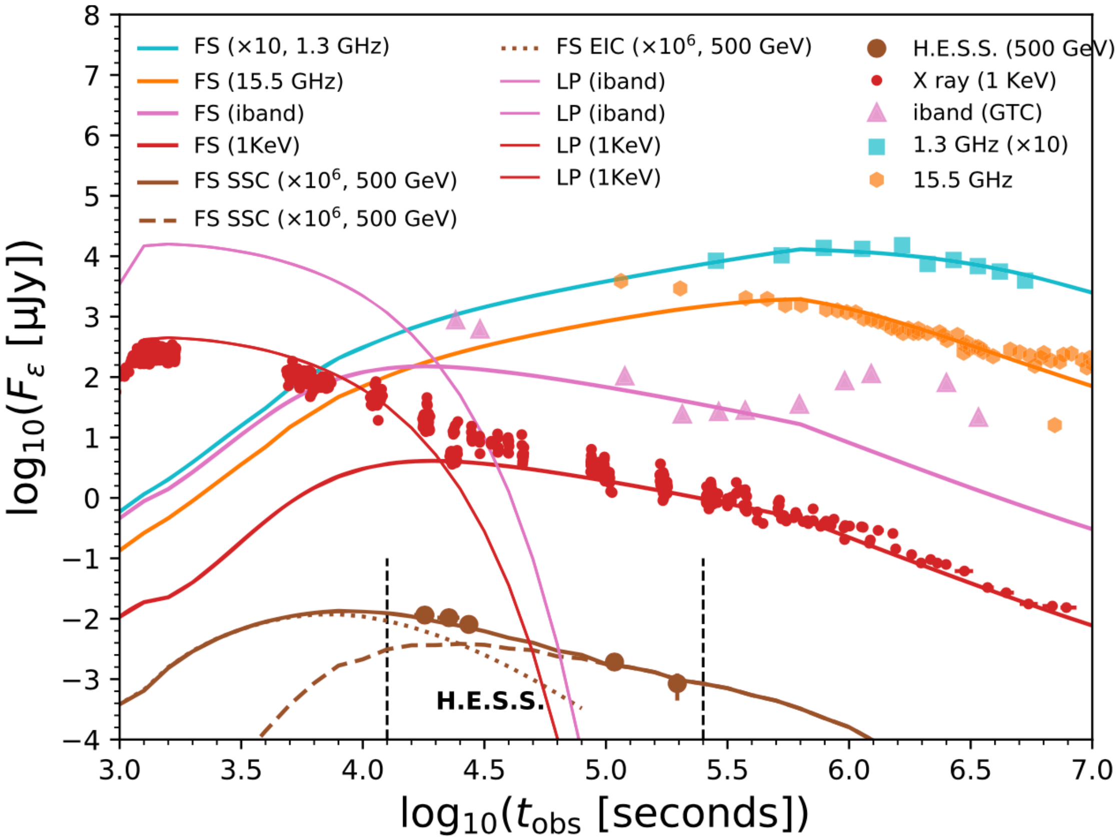
The late time X-ray flare can be fitted with Noris model

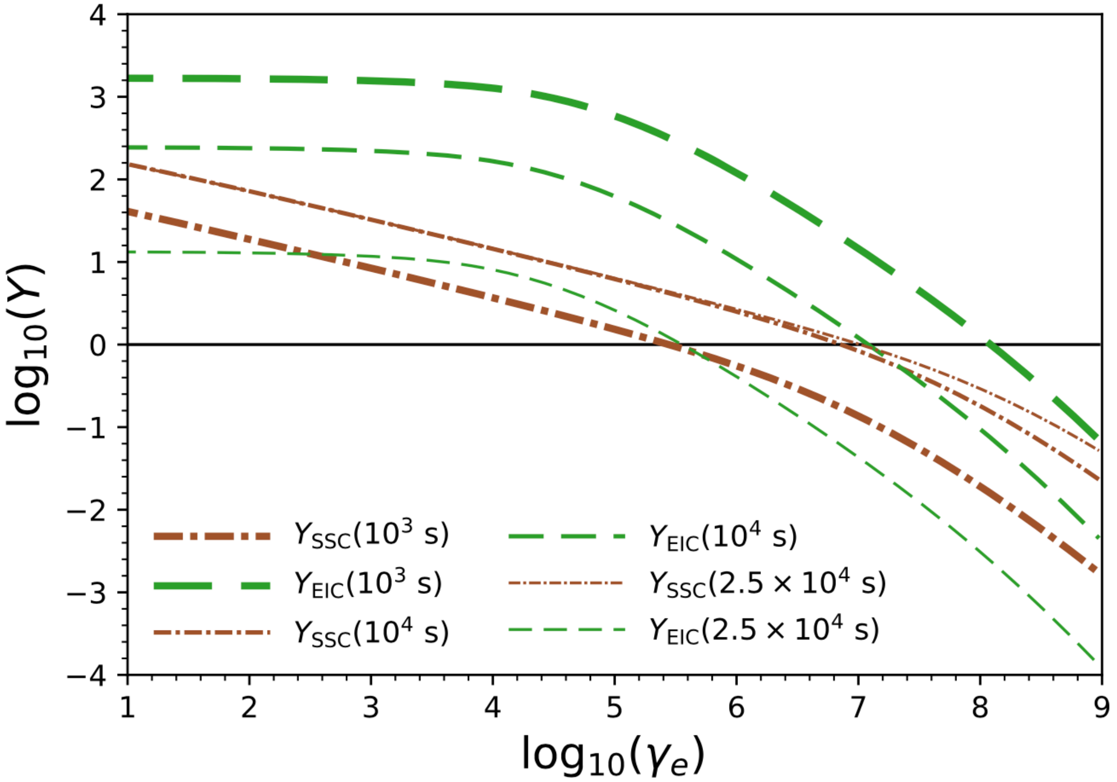
$$F^{\rm fl}_{\varepsilon_b}(t) = A\lambda e^{-\frac{\tau_1}{t-t_i}-\frac{t-t_i}{\tau_2}}$$

$$F^{\rm fl}_E = F^{\rm fl}_{E_b}(t)\begin{cases}\left(\frac{E}{E_b}\right)^{-\alpha+1}, & E<E_b\\ \left(\frac{E}{E_b}\right)^{-\beta+1}, & E>E_b\end{cases},$$

The SSC (EIC) Compton parameter depends on the ratio of comoving photon energy density and magnetic energy density

$$Y_{\rm SSC(EIC)}(\gamma_e) \approx \frac{P_{\rm SSC(EIC)}}{P_{\rm syn}} \sim \frac{U'_{\rm syn(FL)}[\varepsilon' < \varepsilon'_{\rm KN}]}{U'_{\rm B}}$$





BTZ, Murase, Veres and Meszaros, 2021

GRB 190829A - External-inverse Compton scenario

Seed photons from long-lasting central engine

Dynamical evolution

$$\mathcal{E}_{\rm tot} = \Gamma M_{\rm ej} c^2 + \Gamma m c^2 + \frac{\hat{\gamma}\Gamma^2 - \hat{\gamma} + 1}{\Gamma}\mathcal{E}'_{\rm int}$$

Nava et al, 2013

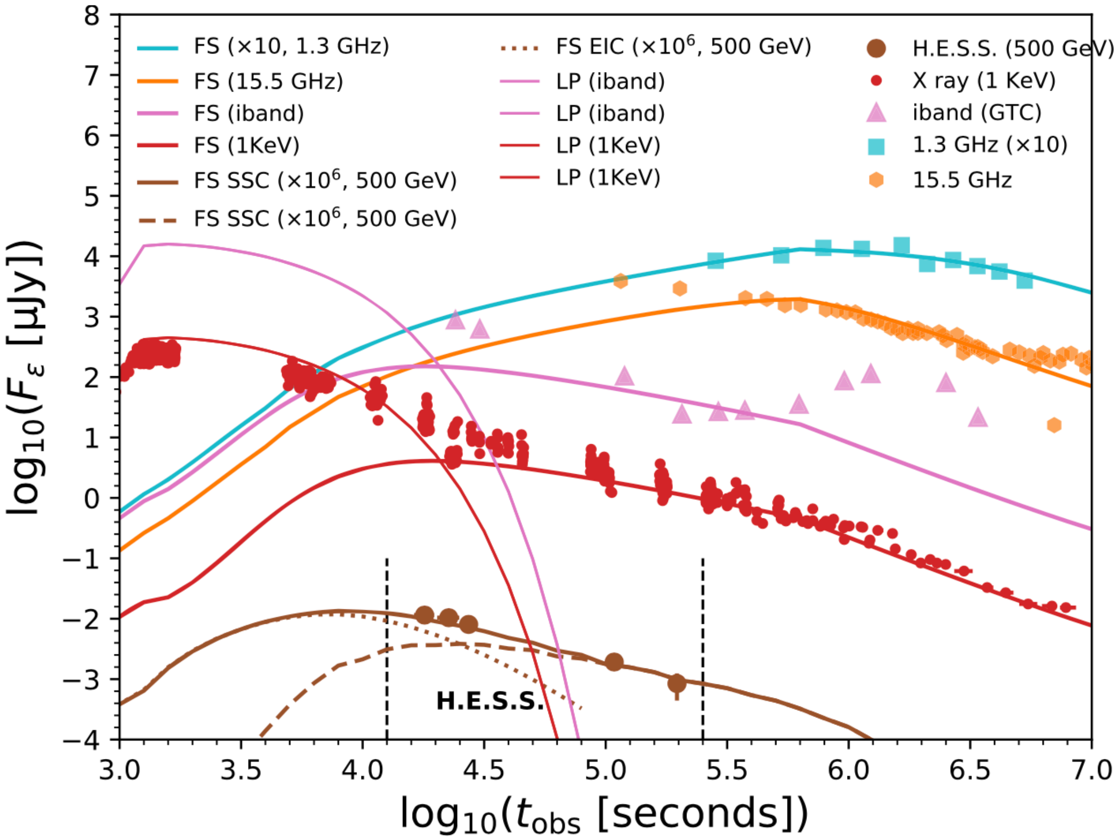
Non-thermal electron distribution

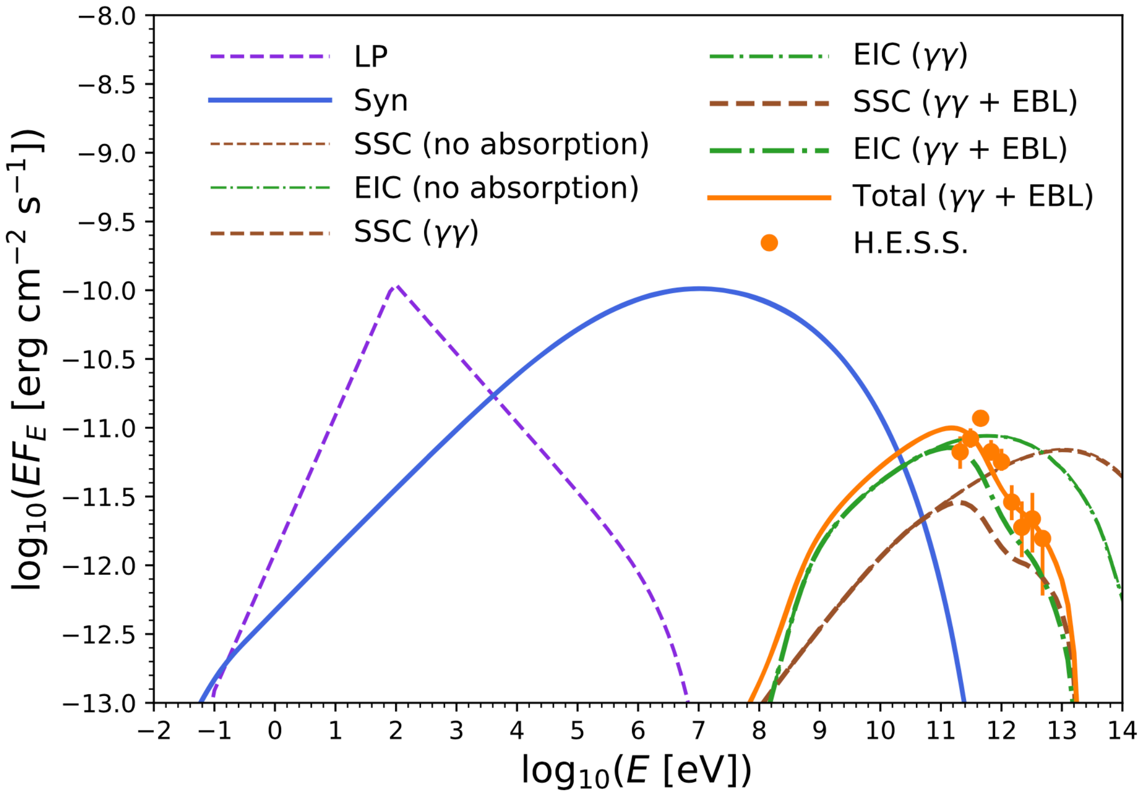
$$\frac{\partial n_{\gamma_e}(t')}{\partial t'} + \frac{\partial}{\partial \gamma_e}\left(n_{\gamma_e}(t')\dot{\gamma}_e\right) + \frac{n_{\gamma_e}(t')}{t'_{\rm esc}} = \dot{n}^{\rm inj}_{\gamma_e}(t'),$$

Anisotropic inverse Compton scattering

Integration over equal arrival time surface

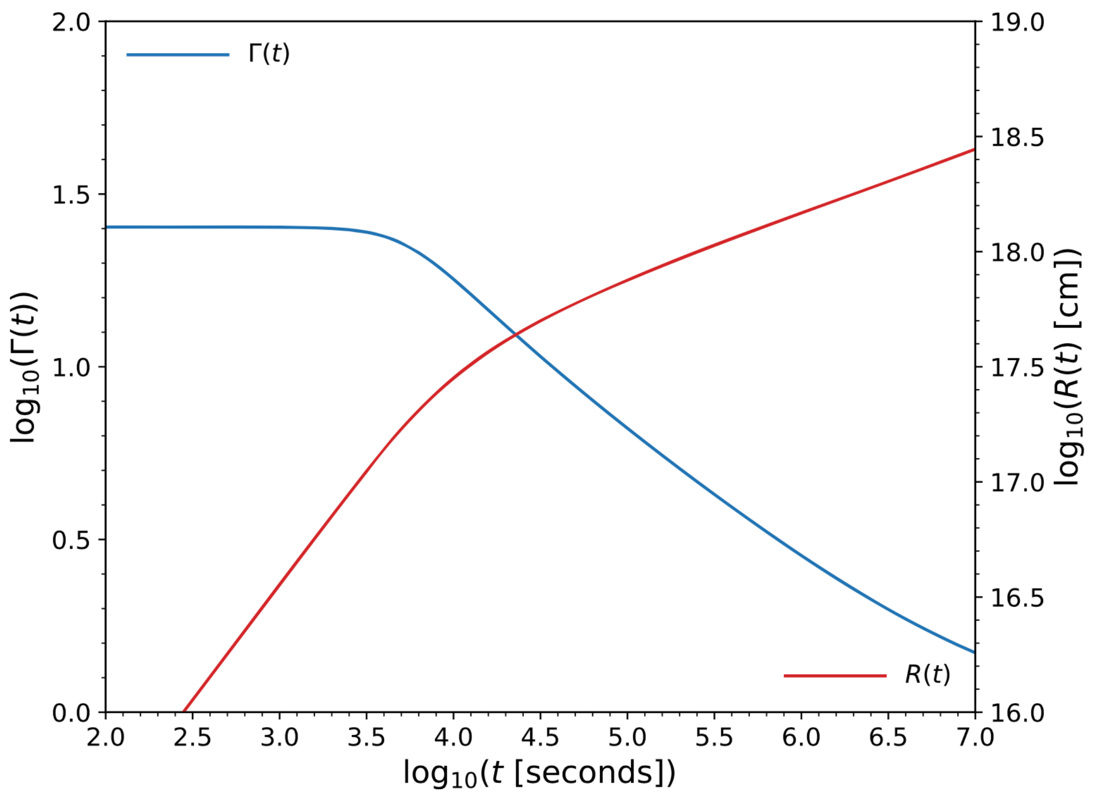
$$F_E(t) = \frac{(1+z)2\pi}{d_L^2}\int_0^\infty dr r^2 \frac{j_{\varepsilon'}(\varepsilon', r, \hat{t})}{\Gamma^3\beta(1-\beta\cos\theta)^2}$$

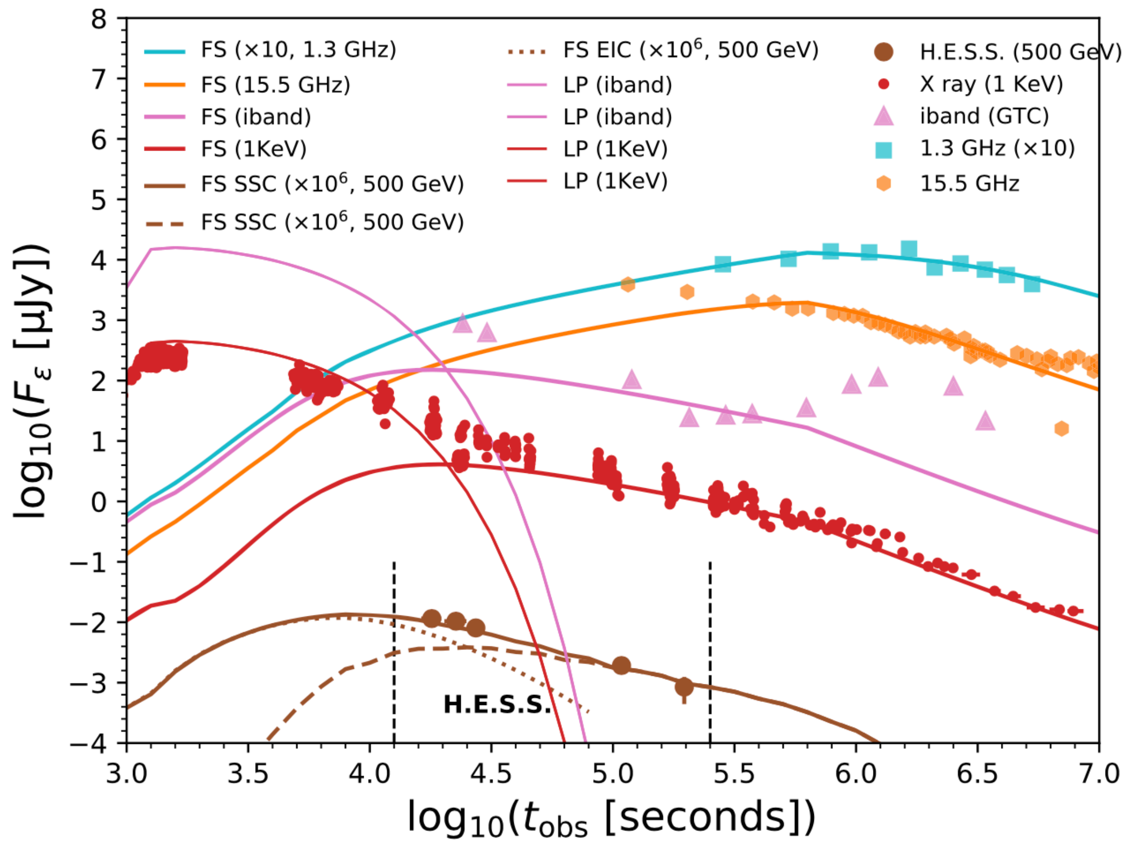




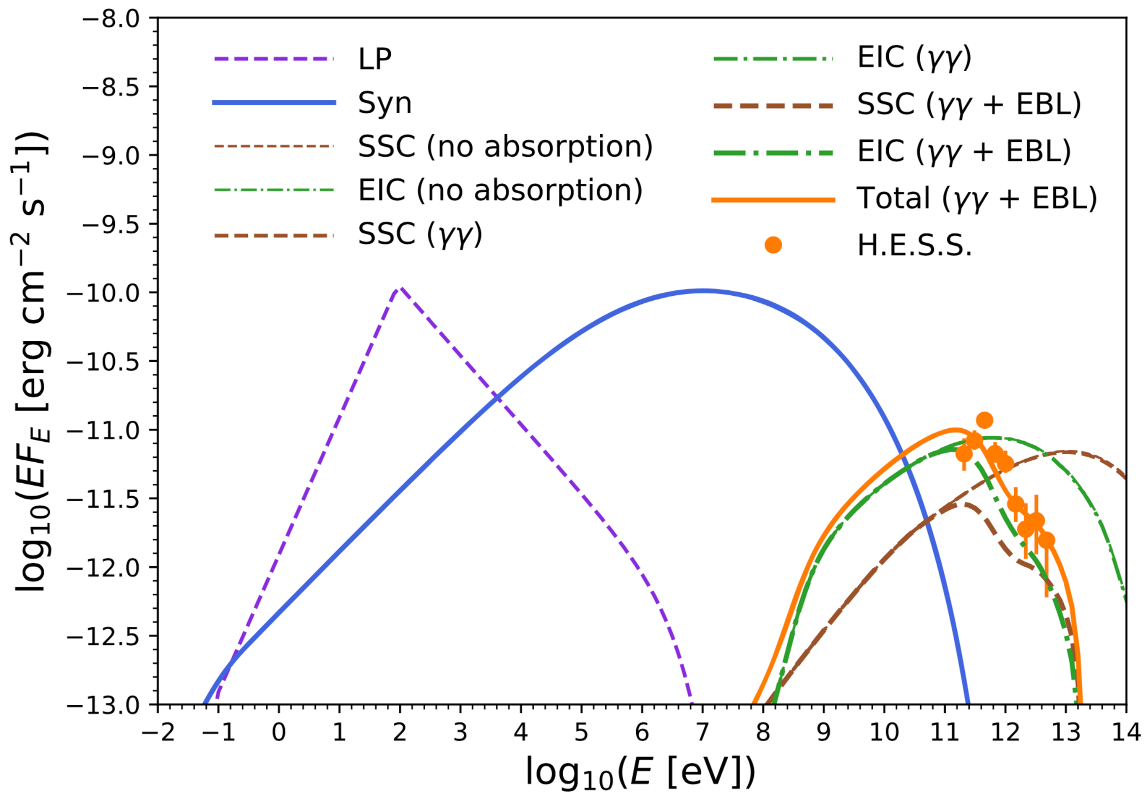
BTZ, Murase, Veres and Meszaros, 2021

GRB 190829A - External-inverse Compton scenario





However, observations implicate initial Lorentz factor Gamma ~ 10



parameters are $\mathcal{E}_k = 9.8 \times 10^{51}$ erg, $n_{\rm ex} = 0.09\ \mathrm{cm}^{-3}$, $\epsilon_e = 0.39$, $f_e = 0.34$, $\epsilon_B = 8.7 \times 10^{-5}$, $s = 2.1$, $\theta_j = 0.2$, $\Gamma_0 = 25$, $\alpha = 1$, $\beta = 2.5$, and $E_b = 100$ eV

BTZ, Murase, Veres and Meszaros, 2021

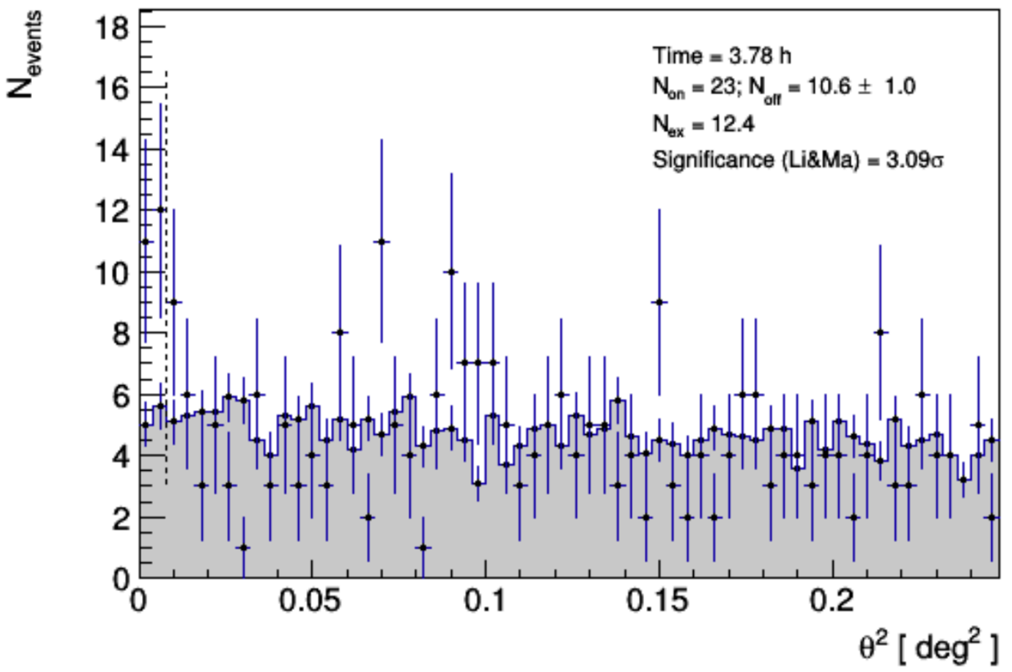
Short GRB 160821B - Synchrotron Self-Compton Scenario

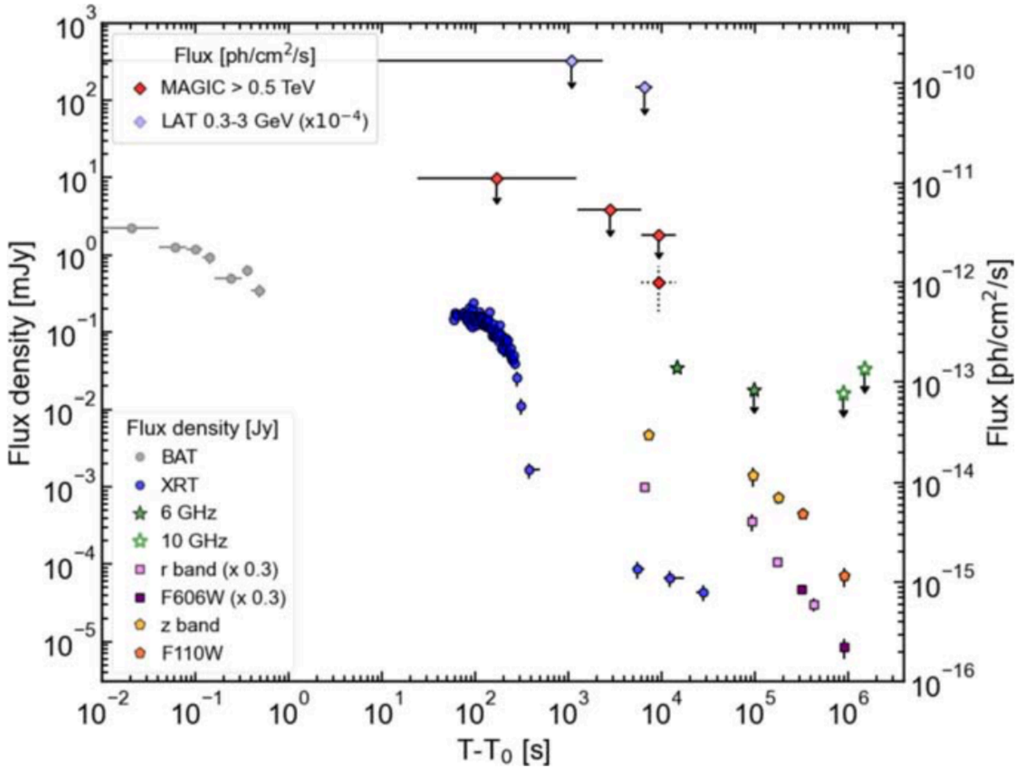
Short GRB 160821B

Redshift: $z = 0.162$

Observations at ~ 1.7 hour affected by clouds

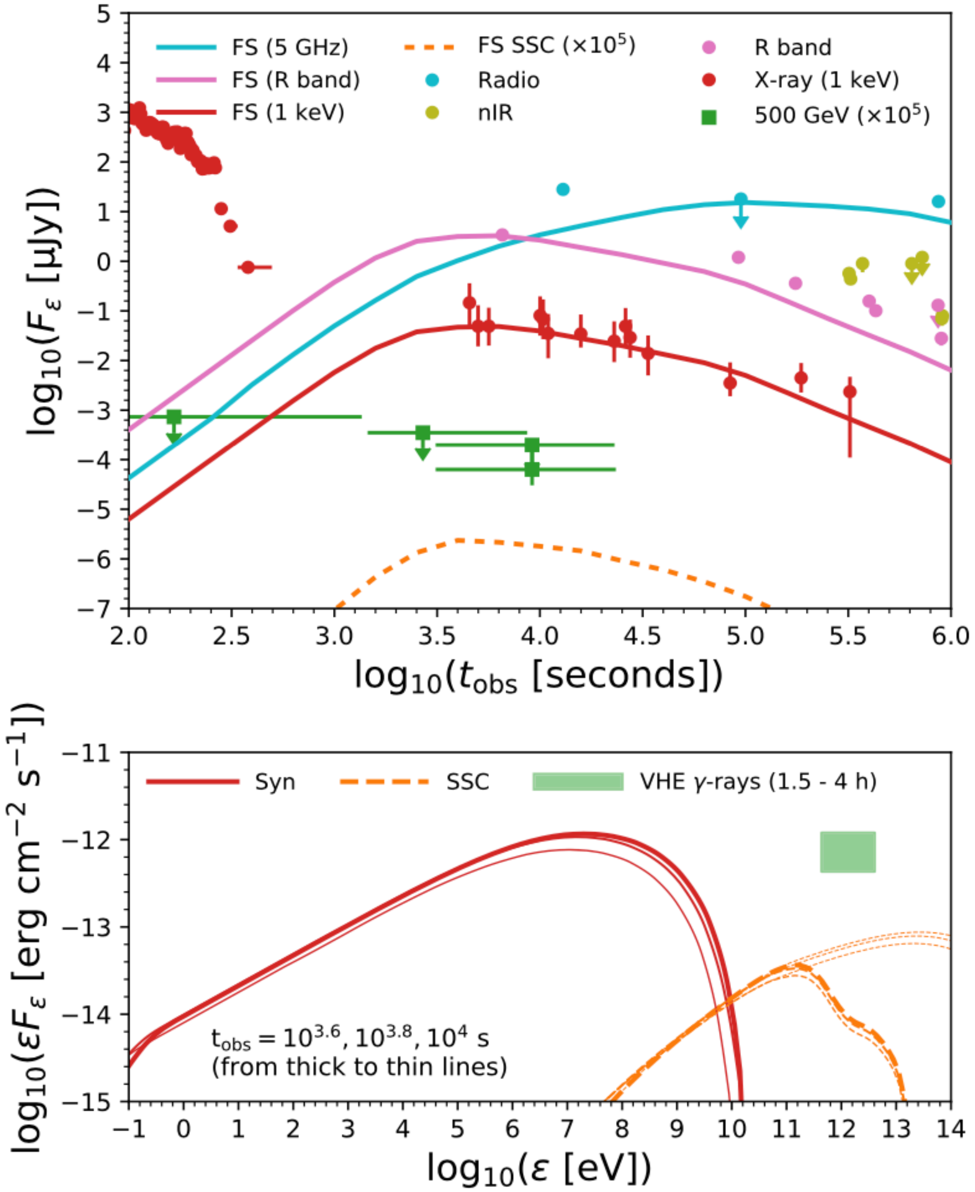
Observations at ~ 3.7 hour

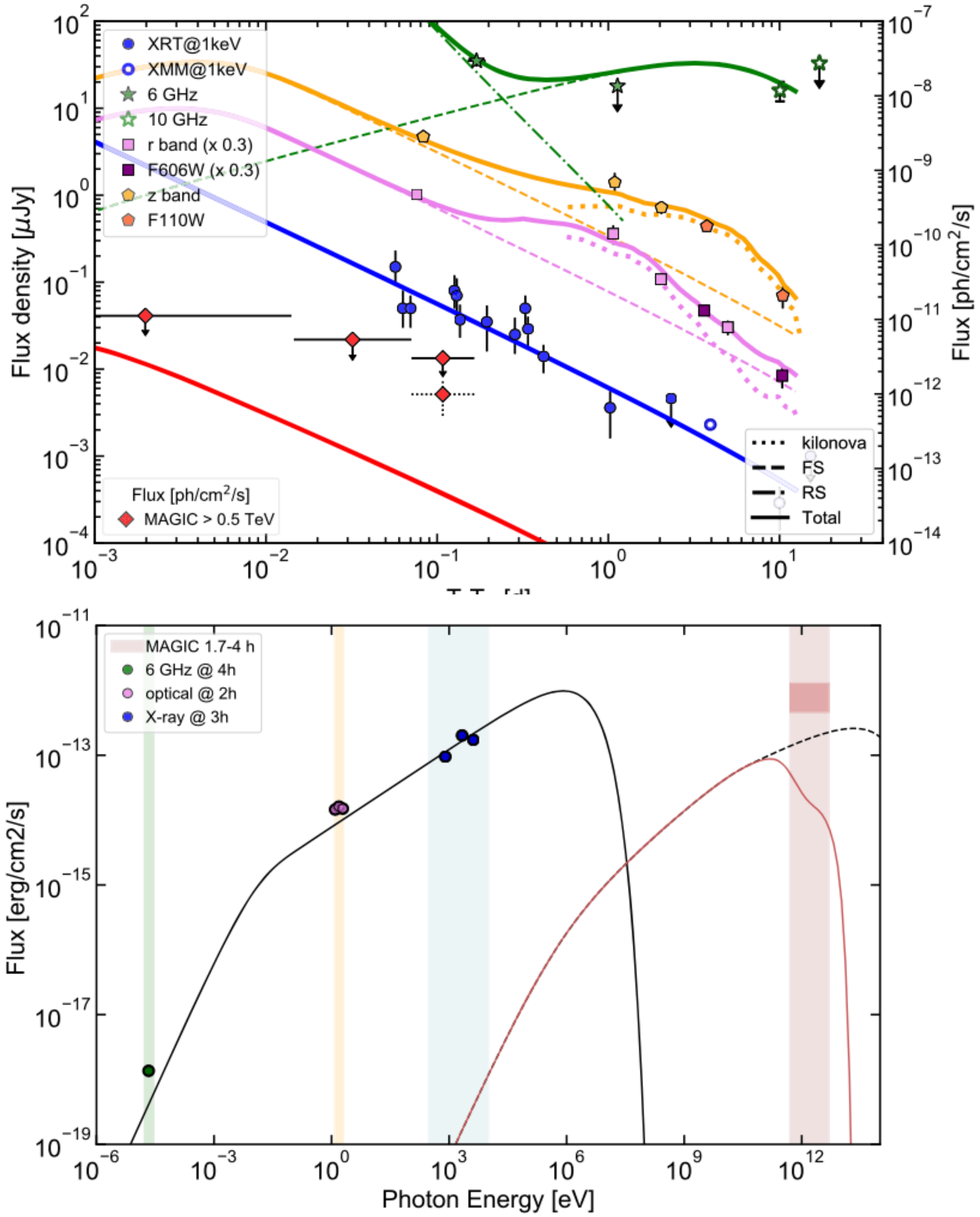




The MAGIC Collaboration, 2021

Short GRB 160821B - Synchrotron Self-Compton Scenario





BTZ, Murase, Yuan, Kimura and Meszaros, 2021

The MAGIC Collaboration, 2021

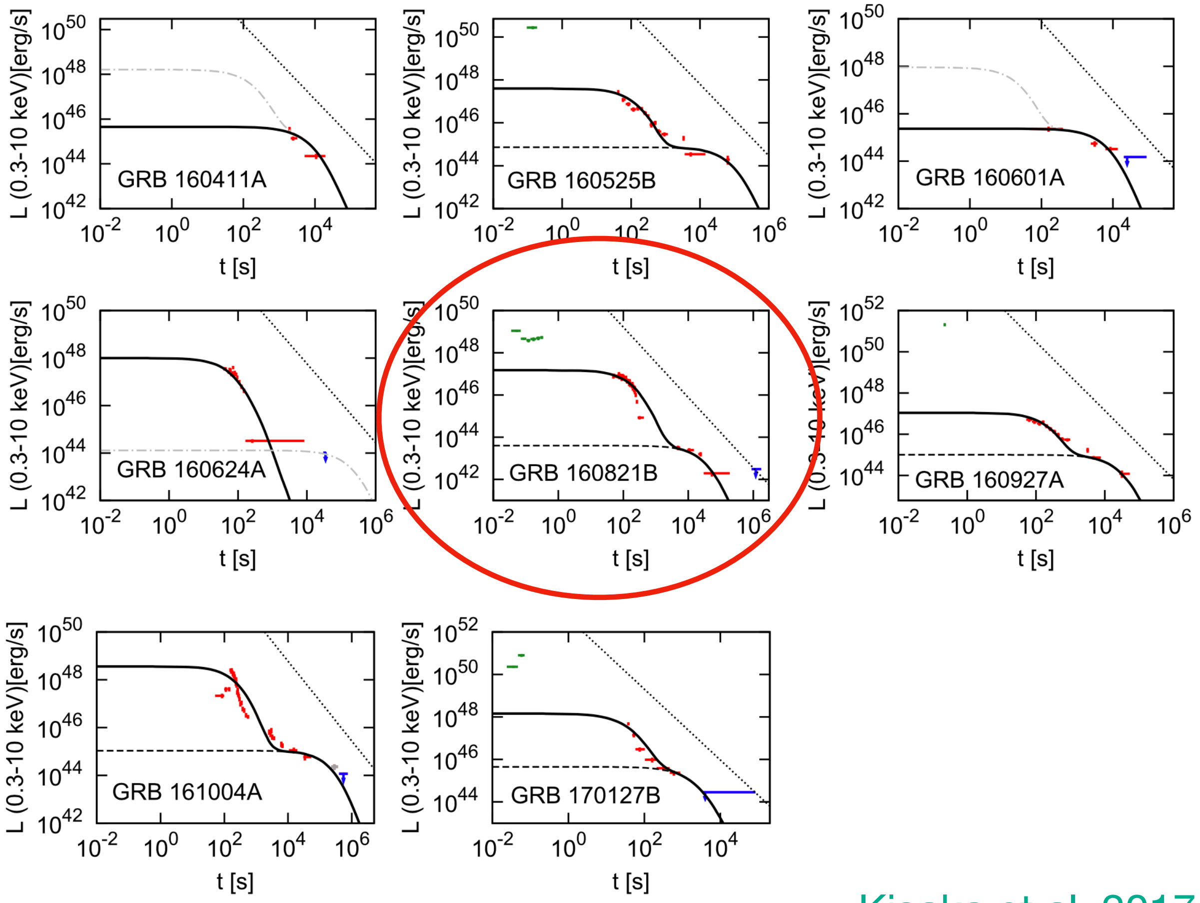
The SSC model unable to explain the large VHE flux observed by MAGIC

Melici and Nava, 2022

	E_k erg	$\log(\epsilon_e)$	$\log(\epsilon_B)$	$\log(n)$ cm^{-3}	p	ξ_e	θ_j rad
MAGIC Coll.	10^{51}–10^{52}	$[-1; -0.1]$	$[-5.5; -0.8]$	$[-4.85; -0.24]$	2.2–2.35	1	/
Troja + 2019	10^{50}–10^{51}	$[-0.39; -0.05]$	$[-3.1; -1.1]$	$[-4.2; -1.7]$	2.26–2.39	1	0.08–0.50
Zhang + 2021 (SSC)	3×10^{51}	-0.52	-5	-1.3	2.3	0.5	0.15

Short GRB 160821B - Late-prompt emission

The extended and plateau emission



Kisaka et al, 2017

Phenomenological formula the extended and plateau emission

$$L_{\rm EE}(t) = L_{b,\rm EE}\left(1+\frac{t}{t_{\rm EE}}\right)^{-\delta_{\rm EE}} \qquad \delta_{\rm EE}\simeq 10$$

$$L_{b,\rm EE}\simeq 6\times 10^{48}\ {\rm erg\ s^{-1}} \qquad t_{\rm EE}\simeq 4\times 10^{2}\ {\rm s}$$

$$L_{\rm PL}(t) = L_{b,\rm PL}\left(\frac{t}{t_{\rm PL}}\right)^{-\gamma_{\rm PL}}\left(1+\frac{t}{t_{\rm PL}}\right)^{-\delta_{\rm PL}} \qquad \delta_{\rm PL}=20/3$$

$$L_{b,\rm PL}\simeq 4\times 10^{43}\ {\rm erg\ s^{-1}} \qquad t_{\rm PL}\simeq 2\times 10^{5}$$

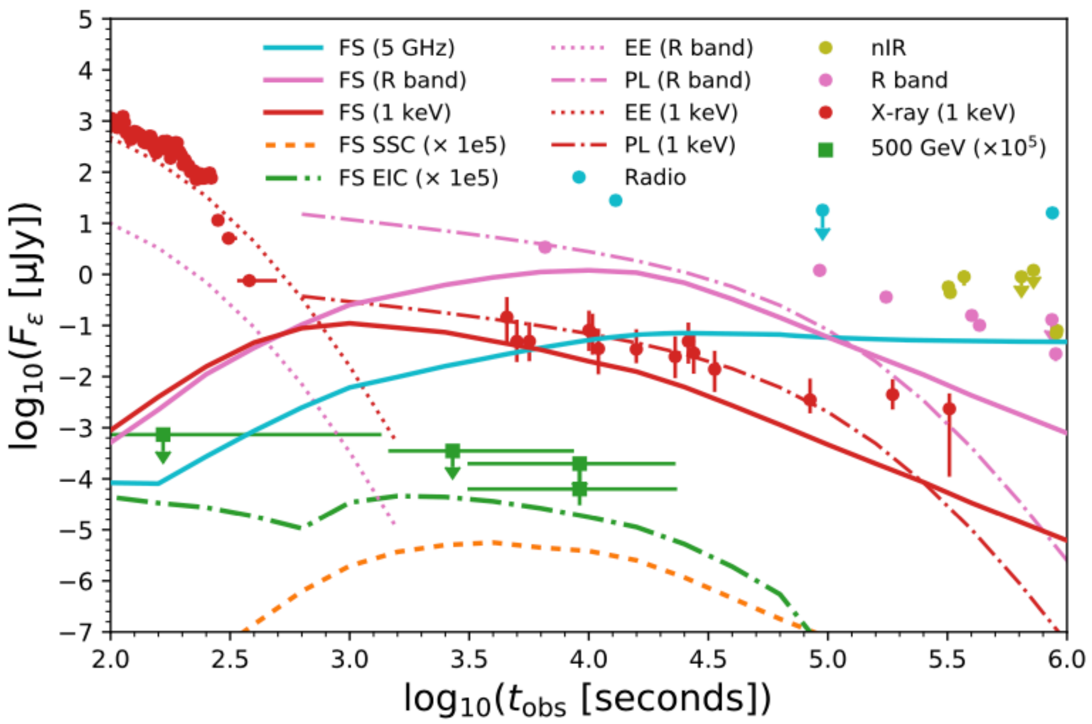
The index is steeper than predicted from fallback accretion in order to fit the data

Kisaka & Ioka 2015

Short GRB 160821B - External-inverse Compton scenario

The EIC light curve is usually flatter than the SSC light curve

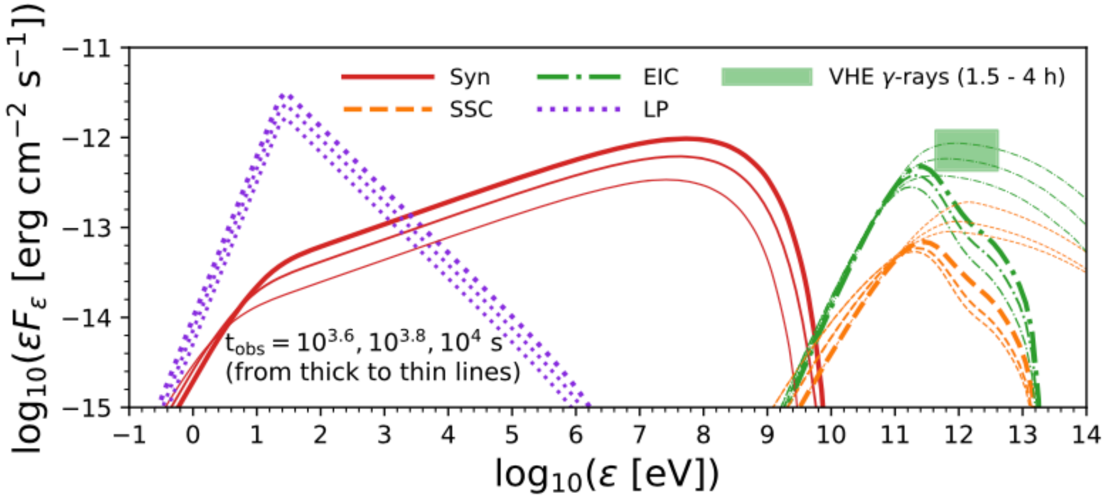
The transition of the seed photons coming from the extended emission to those from the plateau emission is seen in the EIC light curve



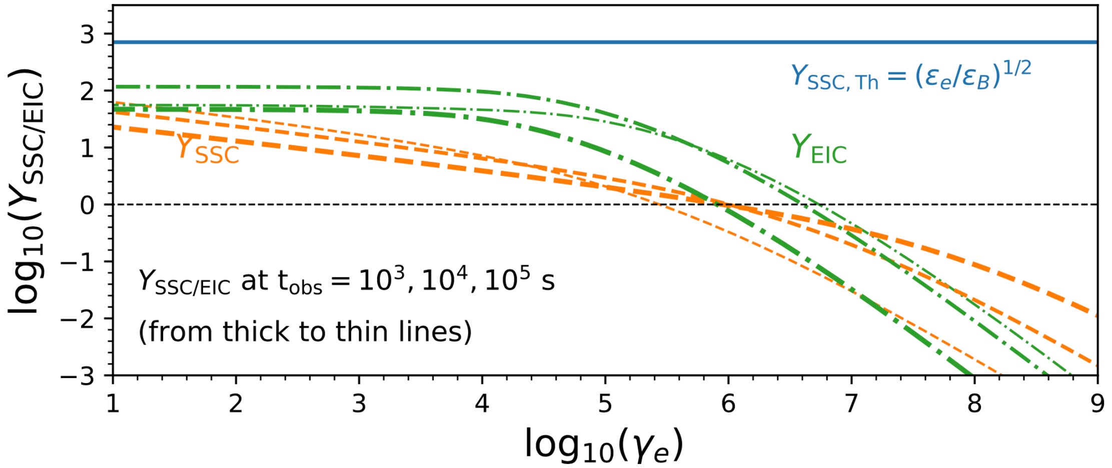
The predicted flux of VHE gamma-rays is

$$\sim 10^{-12}\ \text{erg cm}^{-2}\ \text{s}^{-1}$$

The EIC emission is brighter than SSC emission



The IC scattering with late-prompt plateau photons is between the Thomson and Klein-Nishina regime for electrons with Lorentz factors ~ 1E4 - 1E6

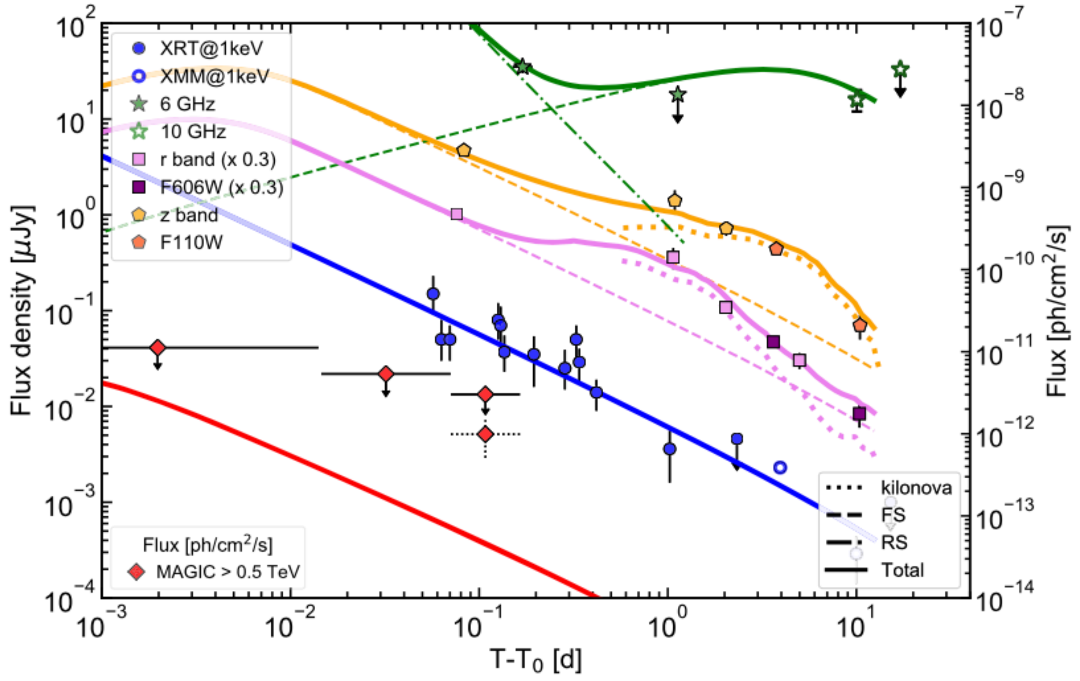


BTZ, Murase, Yuan, Kimura, Meszaros, 2021

VHE gamma-rays from up-scattered kilonova photons

If electrons accelerated in the prolonged relativistic jet and dissipation region is inside the kilonova ejecta

GRB 160821B



The temptation of kilonova emission

$$T_{\rm KN}(t) \approx T_{\rm KN,day}(t/{\rm day})^{-0.8} \simeq 2.8 \times 10^4\ {\rm K}$$

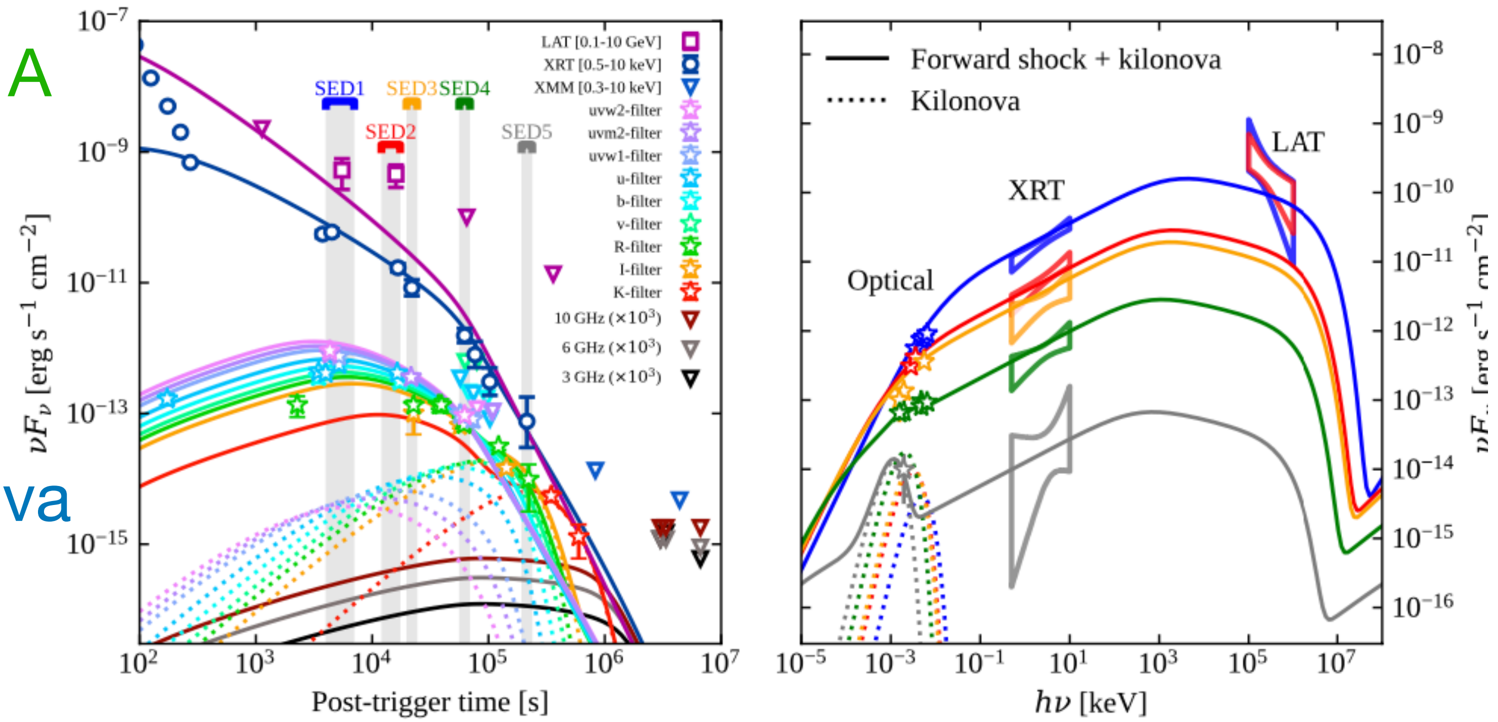
The break energy due to Klein-Nishina effect

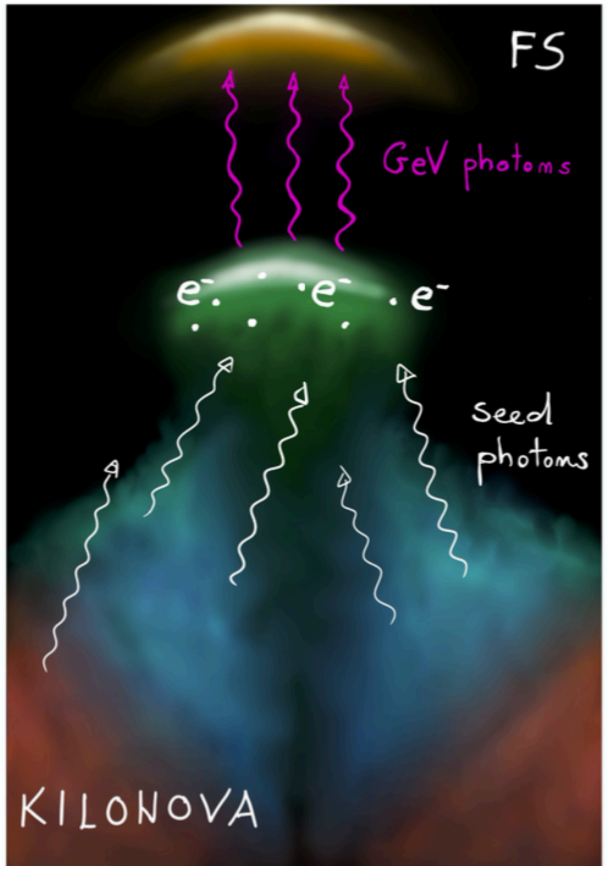
$$\varepsilon_{\rm KN} \approx m_e^2 c^4/(2.8 k_B T_{\rm KN}) \sim 40\ {\rm GeV}$$

It is challenging to explain the MAGIC data !

Short GRB 211211A

A source of hot electrons reside nearby the kilo nova





Mei et al, 2022, arXiv: 2205.08566

Summary

The detection of VHE gamma-rays from GRBs is increasing

Except from standard GRBs, low luminosity GRBs and short GRB have been detected at VHE band

Low-luminosity GRBs (GRB 190829A)

The simple SSC scenario difficult to explain

The EIC scenario can explanation of observed VHE gamma-rays

The study of VHE gamma-rays is helpful to understand sources of UHECR nuclei

Short GRBs (GRB 160821B)

The explanation of VHE gamma-rays observed by MAGIC is challenging

The EIC scenario can provide better option over SSC

Up-scattered kilonova photons to GeV energy range maybe observed